2

SOME ASPECTS OF THE PETROLOGY OF THE ISLE OF RHUM

By

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ABSTRACT

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The acid rocks of the west of Rhum, previously considered to be one petrological unit designated 'granophyre', have been divided into two petrographically and geographically distinct units; a core of microgranite is surrounded by an outer zone of graphophyre. Along most of its northern boundary the graphophyre has been thrust over Torridonian Sandstone. Along a short length of the contact, however, no faulting has occurred and the graphophyre grades into the Torridonian Sandstone through a belt of transitional rocks. These transitional rocks are divisible into five zones which are interpreted as marking successive stages in the conversion of the Torridonian into graphophyre. The graphophyre grades inwards into the microgranite which is believed to represent a still more advanced stage of metasomatism. The production of the microgranite from the Torridonian has been achieved by the enrichment of the latter in Al, Na, Fe, Ca, K, Ti, Mn and P, at the expense of Si. The excess Si has been driven outwards and fixed as an acid front in the bleached and indurated Torridonian Sandstone to the north. Seven small dolerite sills and several basalt dykes had been intruded into this part of the Torridonian before its conversion to microgranite and graphophyre. These basic intrusions /

sions have suffered considerable metamorphism involving the addition of various constituents, principally Na.

The petrography and internal structures of the basic plutonic rocks of the west of Rhum are described; the harrisite mass is divided into six zones and the gabbro into two. The lower zone of the gabbro consists of an earlier coarse gabbro and a later fine gabbro. The fine gabbro was injected from below into almost horizontal parting planes in the coarse gabbro and forms a series of sheets the members of which are a few inches thick and a few inches apart. This alteration of fine and coarse layers gives the lower zone of the gabbro a highly banded appearance.

The contact between the graphophyre and the basic plutonic rocks to the east is everywhere marked by a narrow zone of hybrid rocks against which both the basic plutonic rocks and the graphophyre have been metamorphosed. These hybrids are interpreted as highly metamorphosed fragmental rocks occurring along a faulted juntion up which streams of hot gases were passing. The hybrid rocks are believed to have been of both cataclastic and pyroclastic derivation; although many fragments were derived from the wall rocks locally, some were transported for considerable distances. The southern and central parts of the narrow zone of hybrid rocks /

rocks are believed to mark the continuation of the ring-fault which is well known in eastern Rhum. The northern hybrid rocks were probably developed along a fault which intersected the western continuation of the ring-fault tangentially.

A small Tertiary vent, which cuts the ring-fault in the east of Rhum, is described. The hybrid rocks which occupy this vent are very similar to those found between the graphophyre and the basic plutonic rocks in the west of the island but they are somewhat finer in grain. The hybrids in the vent are fragmental rocks highly metamorphosed by rising gases at temperatures in excess of $1,000^{\circ}C$. These gases have enriched the vent rocks in K, Na, Ca, Al, Si, and P, and the contiguous Torridonian Sandstone in the same elements together with Fe, Mg, and water.

The rocks of the four Tertiary volcanic outliers in the west of Rhum have been correlated and a succession, nearly 1,700 feet in thickness, has been synthesised from the combined data. The volcanic rocks have been shown to lie unconformably upon the graphophyre.

The post-granitic minor intrusions of the west of Rhum have been divided into six distinct rock types. Two of these, viz. mugearite-tachylyte and augite-andesite, have not previously been recognised in this part of the island.

CONTENTS

VI /

I. INTRODUCTION

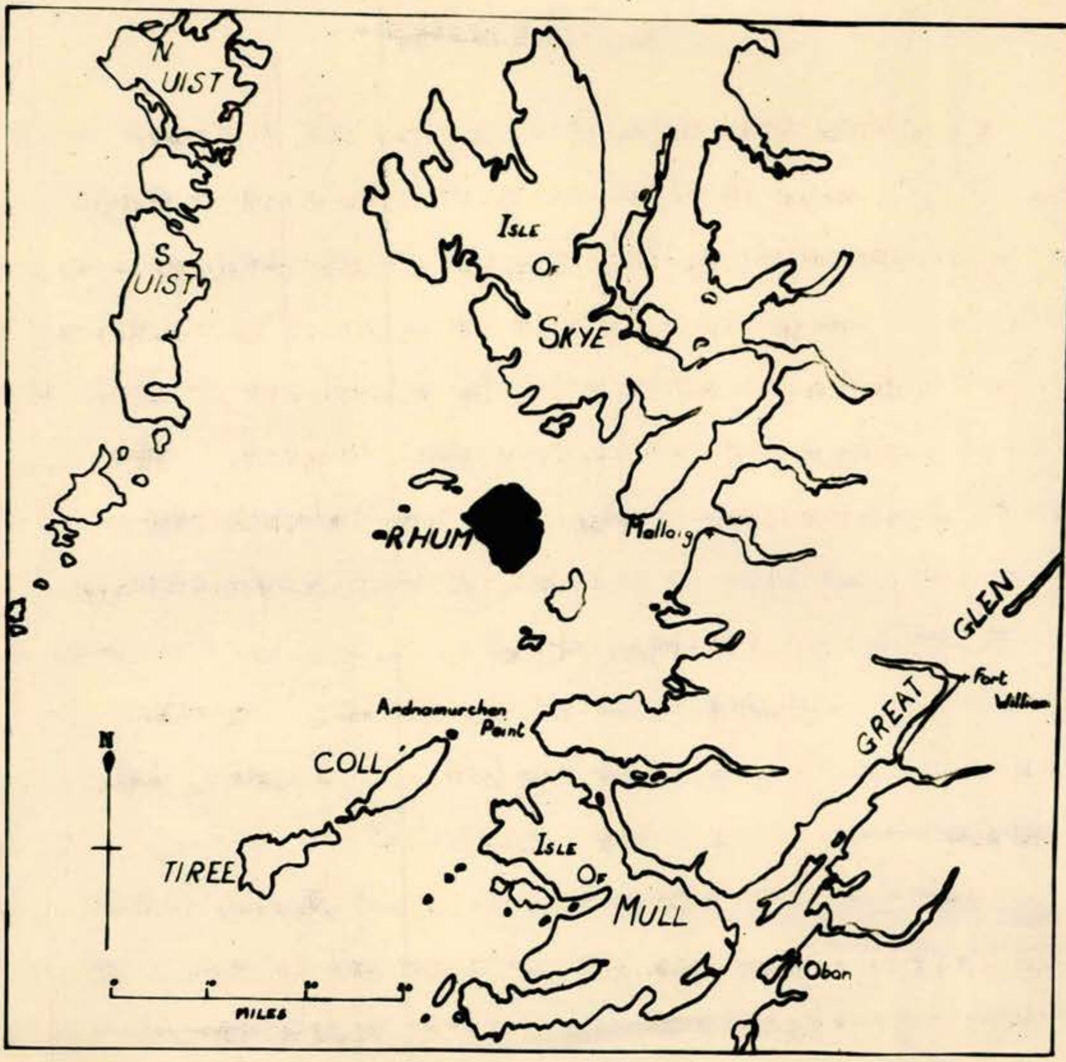

Fig. 1. Sketch-map of a part of the western coast of Scotland showing the position of the Isle of Rhum in relation to the neighbouring islands and the mainland.

I. INTRODUCTION

The mountainous Isle of Rhum lies off the west coast of Scotland, some 15 miles north of Ardnamurchan Point and 8 miles south of Skye, (see Fig. 1). It occupies a central position in the group of the Small Isles of Inverness-shire.

The maximum dimensions of the island are 8¾ miles from north to south and 8½ miles from east to west. The total area is approximately 42 square miles; except for 300 acres of arable land this is entirely devoted to deer-forest.

There is considerable topographic contrast between the northern and southern parts of the island. Whereas the former is moorland nowhere reaching 1,000 feet, the latter is mountainous, the highest point, Askival, rising to 2,659 feet above the sea. This topographic contrast reflects the different geology of the two parts of the island. The northern part consists of Torridonian strata dipping gently to the north and west; the southern part forms one of the well-known Tertiary complexes which occur along the western seaboard of Scotland.

The complex has been emplaced into the Torridonian Sandstone and is unconformably covered by outliers of Tertiary lavas. The age of the complex cannot therefore be determined from /

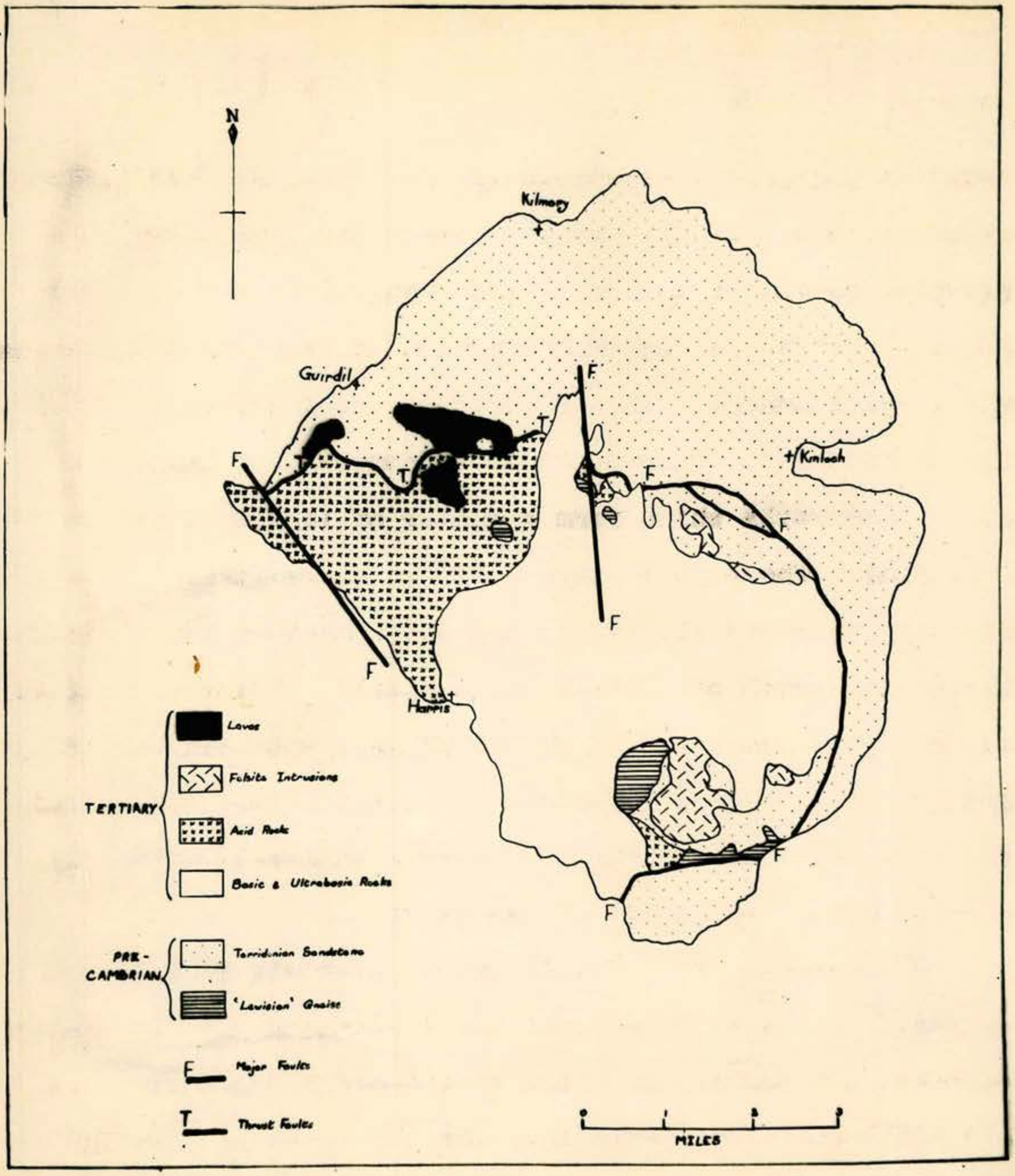

Fig. 2. Geological sketch-map of Rhum. A small patch of Trias, lying unconformably on Torridonian Sandstone in the north-west of the island, and numerous minor intrusions have been omitted.

from its geological relationships and since no fossiliferous deposits have been discovered between the lava flows, the accepted dating of the complex as Lower Tertiary is based on analogies with the similar complexes of Skye and Ardnamurchan. The complex consists of two distinct portions, (see Fig. 2). The eastern and larger of these is composed of basic and ultrabasic rocks which form a number of layers of varied composition. The highest layers now preserved are alternations of peridotite and allivalite and these make up the summits and upper slopes of Askival and Allival. Towards the west successively lower layers, first of harrisite and then of gabbro, are exposed. Towards the east, on the other hand, the peridotite and allivalite overlie the gabbro directly, without the intervention of harrisite.

The western part of the complex consists of acid rocks in which are included several small metamorphosed lenticles of basic and ultrabasic rocks that closely resemble those of the small sills intrusive into the Torridonian. On the north the acid rocks are bounded by the Torridonian Sandstone, the contact dipping to the south, steeply in its eastern parts but less so in the west. The acid rocks adjoin the basic and ultrabasic part of the complex to the east along an almost vertical contact which is marked by a well-developed zone of net-veining. /

net-veining. Sparse, metamorphosed basalt dykes are included in the acid rocks and represent the remnants of a pre-plutonic swarm. Outside the limits of the complex the rocks of this swarm cannot be distinguished from the much more numerous post-plutonic dykes.

A large mass of felsite occurs on the southern margin of the basic and ultrabasic rocks. Smaller masses of felsite occur at intervals on or near the outcrop of the arcuate fault of considerable throw which marks the approximate eastern boundary of the complex. A small mass of microgranite and associated 'hybrid rocks' also occurs on the outcrop of this fault.

In the western part of the island outliers of Tertiary volcanic rocks rest unconformably upon Torridonian Sandstone and Tertiary acid rocks. The volcanic succession comprises basaltic and mugearitic lavas and two horizons of fluviatile conglomerates.

A post-plutonic dyke-swarm, often cited as a text-book example of a radial swarm, cuts all the above mentioned rocks. Most of the dykes are basaltic in composition, dykes of other compositions being rare. A few inclined basaltic sheets, of unknown age relative to the dykes, are present and have been interpreted as a series of cone-sheets.

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A peculiar banded rock, described by Harker (1908) pp. 105-114) as "gneiss, hybrid between granophyre and eucrite", forms nine patches within the margins of the complex, only one of which, however, is of considerable size. More recently Tilley (1944 pp. 129-131) has interpreted this rock as Lewisian Gneiss.

Numerous faults cut the Tertiary plutonic and volcanic rocks.

Recent deposits, comprising boulder clay, raised beach deposits, alluvium, peat, and blown sand, are common on Rhum and conceal much of the underlying rock. The gabbros are particularly poorly exposed and their marginal relationships are rarely visible. The other rocks, however, are often well-exposed, especially in the coastal sections.

The bulk of the research has been carried out over an area of approximately 12½ square miles in the western part of the island. A much smaller area in the east of Rhum has also been investigated. (See Fig. 6).

The western main area investigated consists of four distinct geological units each of which has its characteristics topography. The largest of these units forms the western part of the area and is underlain by acid rocks. It varies in /

in elevation from sea-level to heights of over 1,800 feet inland. On its seaward margin it is bounded by cliffs which culminate at Wreck Bay at a height of almost 1,000 feet. Near the north-western corner of the unit there is a series of northward-facing scarps with scree-slopes at their base. Over the remainder of the unit the slopes are smooth and the hills are rounded. Loose blocks of the acid rocks cover the high ground; the floors of the wide, glaciated valleys are obscured by peat. Accordingly the acid rocks are generally not well-exposed. The most conspicuous features of this area are the cliff-bound outliers of Tertiary lavas and the small lenticles of basic and ultrabasic rocks included in, and metamorphosed by, the acid rocks.

The northern unit is a moorland plateau rising to 1,050 feet and floored by Torridonian Sandstone. Two outliers of Tertiary volcanic rocks rise above the general level of the plateau and form the hills of Fionchra (c. 1,650 feet) and Bloodstone Hill (1,293 feet).

In the eastern unit the topography is characterised by rugged knolls and many small cliffs. The underlying rocks are peridotite in the east and harrisite in the west and south. The land rises from sea-level in the south to a maximum height of 1,350 feet in the centre of the unit but declines again to the /

the north to elevations of 500 or 600 feet.

The southern unit is floored by gabbro. It has an average elevation of only 200 feet and it is extensively covered by Pleistocene and Recent deposits. Outcrops are almost entirely confined to the coast and to two stream-sections.

The drainage of the main research area is roughly radial. On the south-west the area is drained by several short streams into the Atlantic; on the north the water is carried into the Sound of Canna by the Allt Camas n-Atha, the Guirdil River, and the Glen Shellesder Burn; on the north-east the area drains into the old headwaters of the Kilmory River which, however, have been artifically diverted to the Sound of Rhum by the Kinloch River; on the east the area feeds several small streams which flow eastwards to join the Abhainn Sgathaig; on the south the water flows into the Atlantic by means of the Glen Duian River. The Abhainn Rangail, the largest river of Rhum, debouches into the Atlantic in the southern extremity of the area. It receives the waters of the Abhainn Sgathaig but does not otherwise drain any appreciable part of the area.

A very small area in the east of Rhum has also been investigated by the present writer. The north-western part is floored /

floored by gabbro, the central part by microgranite and associated hybrid rocks, and the south-eastern part by Torridonian Sandstone. Apart from the gabbro, the rocks are well-exposed. This area lies some 450 feet above sea level and is drained by tributaries of the Allt na Ba which flows south-south-east into the Sound of Rhum.

Although many geologists have visited Rhum, no detailed investigation has hitherto been made of the acid rocks of the western part of the island. The relationships of these rocks to the Torridonian Sandstone, the basic and ultrabasic rocks, and the superincumbent lavas have, in the past, been similarly neglected. Accordingly it was thoughtdesirable to make a new detailed study of the western part of the island. The small mass of microgranite and associated hybrid rocks, which outcrops on the line of the arcuate fault in the east of the island, has not previously been described.

The principal topics and problems investigated were:-

1. The petrography and petrogenesis of the acid rocks of the west of Rhum and their relationships, firstly, to the Torridonian Sandstone, and, secondly, to the basic and ultrabasic rocks. An investigation into the origin of the zone of 'net-veining', which marks the contact of the acid rocks with the basic and ultrabasic /

ultrabasic rocks, was included.

2. The correlation and stratigraphy of the four outliers of volcanic rocks in the west of Rhum and their relationships to the acid rocks.
3. The petrography of the dykes in the western part of Rhum.
4. The petrography and petrogenesis of a small mass of microgranite and associated hybrid rocks in the east of Rhum.

In the course of the investigation the western part of the island was remapped on a scale of 6 inches to 1 mile. Various small masses of igneous rocks, numerous hitherto unrecorded dykes, and several faults, two of which are of large throw, were discovered together with minor modifications of the geological boundaries, as previously mapped.

The following are the principal conclusions reached as a result of the investigation:-

1. The acid rocks in the west of Rhum consist of two distinct types - graphophyre and microgranite - the distribution of which can be mapped. The contact of the acid rocks with the Torridonian is faulted along most of its length, but a short part of it is transitional. /

transitional. The contact of the acid rocks with the basic and ultrabasic rocks to the east also appears to be faulted; the 'net-veined' zone represents the metamorphosed fault breccia.

2. A volcanic succession, nearly 1,700 feet in thickness, can be synthesised from the rocks of the four volcanic outliers. The volcanic rocks rest unconformably upon the acid rocks.

3. The basalt dykes of the west of Rhum can be divided into six petrographic groups. In addition to the basaltic dykes, augite-andesite and mugearite-tachylyte dykes, not previously known from this part of Rhum, are present in small numbers.

4. The microgranite and associated hybrid rocks in the east of Rhum are metamorphosed pyroclastic rocks which occupy a small vent.

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II. PREVIOUS GEOLOGICAL RESEARCH ON THE ROCKS OF THE ISLE OF RHUM

PREVIOUS GEOLOGICAL RESEARCH ON THE ROCKS OF THE ISLE OF RHUM

Although geological research on the rocks of Rhum commenced in 1819, long intervals have separated the appearance of the various publications and only one comprehensive account of the geology of the whole island has been published.

Dr. John Macculloch (1819) recognised that the red sandstone, which forms the northern and eastern parts of the island was the equivalent of the red sandstone of Applecross and Skye (Torridonian). He identified the rocks of the south and west of Rhum as 'augite-rock' (peridotite), 'massive trap' (gabbro), and 'syenit' (acid rocks), and concluded that these rocks lay above the red sandstone. He described the occurrence of 'stratified trap' (basaltic lava) in the west of Rhum and discovered a new mineral - chlorophaeite - in the amygdales of the lavas on Bloodstone Hill. Macculloch illustrated his account of the geology of Rhum with a map showing the approximate distribution of the main rock types.

Ami Boué (1820) included a shortened version of Macculloch's description of the geology of Rhum in his "Essai Géologique sur l'Écosse", and another summary of Macculloch's work appeared in James Nicol's "Guide to the Geology of Scotland", published in 1844.

L.A. Necker de Saussure traversed Rhum from Kinloch to Guirdil /

Guirdil and described his observations in his "Voyage en Écosse et aux Iles Hébrides" (1821). He commented on the lack of adequate exposures on the lower parts of the island and noted that the (Torridonian) grits near Guirdil dip to the west at 60°. He described at length the semi-precious stones occurring on Bloodstone Hill and mentioned the presence of solid basalt veins and loose pitchstone blocks on the shore at Guirdil. His reference to Rhum concluded with a very short summary of Macculloch's account of 1819.

Professor J. W. Judd, in his four papers (1874, 1885, 1886 and 1889) made important contributions to the geological knowledge of Rhum. Judd realised that the rocks in the south and west were igneous and were related to each other in some close but unspecified way. He pointed out that these rocks resembled those of central Mull and of Ardnamurchan, and he believed that these three areas of similar igneous rocks marked the respective sites of large Hawaiian-type volcanoes. Judd correctly identified the four masses of basaltic rocks in the west of Rhum as lava outliers resting unconformably on both the Torridonian Sandstone and on the plutonic igneous rocks, and discovered felsitic volcanic vents in the south and east of Rhum. He gave the first detailed account of the mineralogy of the basic and ultrabasic rocks; and divided the ultrabasic rocks into six groups on the basis of their mineral content. /

content. Judd's map of the western part of Scotland shows accurately the distribution of the various rock-types on Rhum.

Sir Jethro J.H. Teall (1888) figured and described a 'picrite' (allivalite) from Allival and concluded that its content of feldspar "was too abundant to make the rock a true picrite".

Sir Archibald Geikie published an account of the geology of Rhum in 1897. He rejected Judd's hypothesis that the Tertiary lavas had been erupted from central volcanoes and postulated instead that they had been fed by numerous dyke-fissures. The lava outliers in the west of Rhum he recognised as the remnants of a lava-plateau once continuous over the whole area now occupied by the Small Isles. Geikie divided the plutonic rocks of Rhum into an earlier gabbroic portion in the east and a later granitic portion in the west and he recognised and described the net-veined zone along the contact of the two portions. The disposition of the layered gabbroic rocks he likened to the "terraced basalts of the plateau", and he stated that the various layers differed from each other in their content of pyroxene and olivine. The plagioclase-olivine rocks he styled 'troctolite' and he found that the plagioclase crystals in these rocks were aligned in (what he and Dr. F. H. Hatch considered to be) a flow structure /

structure. From the similarity of the gabbroic rocks of Rhum to the rocks of the Cuillin Hills of Skye, Geikie inferred the relationship of the former to the lava-plateau. "If we could restore the lost portions of the [Rhum] plateau, I believe that we should find the gabbros of Rhum resting on part of the volcanic plateau, and some of the gabbro-beds prolonged as sills between the sheets of basalt".

Geikie named the acid rocks of the west of Rhum "quartz-porphyries becoming felsitic towards their contacts with the adjacent rocks", and maintained that they had intruded and metamorphosed the base of the volcanic pile. The bedded nature of the acid rocks, first recorded by Macculloch in 1819, was re-described by Geikie. He also re-described the felsites of the east of Rhum and noted the breccias which occur between them and the Torridonian Sandstone. Geikie noted the thermal metamorphism of the Torridonian Sandstone in the neighbourhood of the igneous rocks. Finally he recorded a number of basaltic sills and a "pitchstone vein traversing the western slopes of the wide granophyre boss of Orval".

Dr. M.F. Heddle (1901) described the mineralogy of Rhum and noted occurrences of quartz, microcline, labradorite, biotite, enstatite, augite, chrysolite, olivine, chromite, chondrodite, pectolite, celadonite, calcite, rumpfite and chlorophaeite.

Geological /

Geological knowledge of Rhum was greatly extended in the first decade of the twentieth century when Dr. Alfred Harker investigated the whole island on behalf of the Geological Survey. Two preliminary papers appeared in 1903 and 1904 and the complete results of his investigation were published in 1908 as the largest part of the Geological Survey Memoir "The Geology of the Small Isles of Inverness-shire". The Memoir was accompanied in the same year by Sheet 60 of the one inch to a mile Geological Survey Map of Scotland.

Harker divided the Torridonian rocks of Rhum into an upper group of arkoses and grits and a lower group of shales. He maintained that, although the bulk of the Torridonian strata were autochthonous, some of the Torridonian in the east and in the north-west of Rhum were allochthonous and had been thrust into their present positions from the south-east.

Harker considered that the first manifestation of Tertiary igneous activity on Rhum was the eruption of the volcanic rocks. A horizon of fluviatile volcanic conglomerates was found at the base of the volcanic pile and this was succeeded by numerous lava flows, which, in their upper part, contained another, but thinner, horizon of fluviatile volcanic conglomerates. Harker discovered the presence of mugearites in addition to basalts in the four volcanic outliers, but he regarded all the mugearites, and also the central columnar portions /

portions of the basalts, as sills. In consequence, his descriptions of the lavas are disconnected and incomplete. Harker followed Geikie in preference to Judd, firstly, in believing that the lavas had been intruded and metamorphosed by the underlying acid rocks, and secondly, in postulating that the lavas had been fed by dyke-fissures. Harker identified a sparse swarm of basaltic dykes, included in and metamorphosed by the acid rocks, as the feeders of the lavas, and he came to the conclusion that a series of fissures, in the Torridonian rocks and filled by varying proportions of basalt and brecciated Torridonian, were "incipient or aborted channels for the fissure-eruptions of basic lava".

Harker surmised that the plutonic rocks of the island were successively intruded after the volcanic eruptions. In his opinion peridotite and allivalite were intruded first and were followed by eucrite and, at a later date, by granophyre. The basic and ultrabasic rocks he regarded as a complex stratiform laccolith, the various layers of which were successively intruded. In his text-book "The Natural History of the Igneous Rocks" (1909) Harker summarised his conception of the origin of the layered ultrabasic rocks of Rhum:-

"The ultrabasic complex of Rum, best exposed on the flanks of Askival and Allival, illustrates heterogeneity arising from three distinct causes: (i) The rocks consist /

consist principally of olivine and basic felspar, near anorthite, in all relative proportions, pyroxenes being usually of subordinate importance. The whole complex is built up of parallel sheets, usually from 50 to 150 feet thick, which represent distinct intrusions, probably introduced in order from the highest to the lowest. They are alternately richer in olivine (peridotites) and richer in felspar (allivalites). (ii) The several intruded magmas were themselves heterogeneous, consisting of more peridotic and more felspathic portions, which did not mingle freely, but were drawn out to produce a conspicuously banded arrangement within the several sheets. (iii) After intrusion there was a further segregation of parts richer in olivine and in felspar respectively. Flowing movement having ceased, this did not usually take the form of banding, but gave rise to structures of a 'concretionary' kind, traversing the various bands".

Following the intrusion of the layered ultrabasic rocks, Harker considered that the mass of harrisite, which he regarded as veining the overlying peridotite, was intruded in the west of the island at the base of the peridotite-allivalite series. Beneath the harrisite and peridotite-allivalite series lies a layer of eucrite and gabbro; in the east this layer generally /

ally conforms to the stratiform disposition of the complex although it sends veins and tongues into the overlying allivalite and peridotite; in the west, on the other hand, the eucrite and gabbro appear to break through the peridotite and allivalite. Harker arrived at the opinion that the peridotite-allivalite series were brecciated by the transgressive eucrite and gabbro which incorporated the fragments so produced as xenoliths, thus forming the 'intrusion-breccias' at the contact between the basic and ultrabasic rocks. From this evidence he concluded that the gabbro and eucrite were intruded later than the ultrabasic rocks; he surmised that the basic rocks were also intruded later than the harrisite.

The final stage in the plutonic activity was, according to Harker, the intrusion of the acid rocks of the west of the island as a large simple laccolith. The intrusion of acid magma partly destroyed the basic and ultrabasic rocks and gave rise to another series of 'intrusion breccias'. In addition hybrid rocks, styled 'gneiss' by Harker, were believed to have formed as the result of the contamination of the acid magma by the incorporation, fusion, and solution of basic material.

Harker considered that the penultimate stage of the igneous activity of Rhum - the intrusion of numerous basaltic and /

and mugearitic sills - followed the emplacement of the acid rocks.

The final stages of the igneous activity, Harker considered, comprised, firstly, the intrusion of porphyritic quartz-felsites in the south and east of Rhum; secondly, the emplacement of very numerous basic dykes and sheets; thirdly, the intrusion of sparse andesite sheets followed by the introduction of rare peridotite dykes; and finally, the intrusion of pitchstone dykes.

Following the publication of Harker's work, no further research was done on Rhum until 1938 when Dr. F. C. Phillips examined the orientation of the olivine and plagioclase crystals in the peridotites and allivalites respectively. From his examination he concluded that "the stresses acting during the emplacement of an olivine-rich intrusive, already largely crystalline, can develop in the rock precisely those features of the fabric which have been considered to indicate a metamorphic origin".

In 1942, the rocks of the four volcanic outliers in the west of Rhum were re-interpreted by Dr. S. I. Tomkeieff. He concluded that no sills were present in the outliers, the sheets identified by Harker as 'sills' being columnar portions of lava flows. He considered that the mugearites should be re-classified as 'trachybasalts', and postulated that their amygdaloidal /

amygdaloidal nature was caused by the parental magma separating into a water-rich portion, which formed the minerals of the amygdales, and a water-poor portion which formed the glassy matrices of the mugearite flows.

In the same year Dr. Tomkeieff and Dr. K. B. Blackburn published jointly the results of their examination of fragments of fossil wood found in the lavas of Bloodstone Hill. They concluded that the wood "is clearly of the oak-chestnut affinity and that its structure is closely comparable with that of the modern chestnut".

In 1944, a paper by Sir E. B. Bailey entitled "The Tertiary Igneous Tectonics of Rhum, (Inner Hebrides)" appeared. This paper, which was based on four days' field-work, was largely a theoretical re-interpretation of Harker's published maps and petrographic descriptions. Bailey concluded that the dislocation in the east of Rhum, identified by Harker as a thrust-plane, was a ring-fault bounding an area of uplift. The strata in the north-west of the island, which Harker had taken to be allochthonous Torridonian Sandstone, Bailey proved to be Triassic. A three-fold division of the Torridonian Sandstone was put forward by Bailey. He divided Harker's lower division into a basal grit and a shale group; these he correlated, on lithological grounds, with the Diabaig Group of the mainland Torridonian. His third formation - Harker's

upper /

upper group of arkoses and grits he correlated with the Applecross Group. The banded rocks, styled "gneiss, hybrid between granophyre and eucrite" by Harker, were interpreted by Bailey as Lewisian Gneiss. Finally he postulated that the ring-fault had raised the central parts of Rhum as much as 7,000 feet at the commencement of the Tertiary vulcanicity. The peridotites, he maintained, post-dated the uplift and "rose along fissures about a central well to the west of that surrounded by the great initial ring-fault".

Shortly after the appearance of Bailey's paper, Professor C. E. Tilley (1944) published a "Note on the Gneisses of Rum". From an examination of material collected by Harker, Tilley reached the conclusion that "The gneisses free from contact alteration show the essential characters of Lewisian rocks and could be matched with rocks from the northern and southern districts of the foreland".

A brief account of the petrology of the basic and ultra-basic plutonic rocks of Rhum by Dr. S. I. Tomkeieff was published in 1945. He suggested that these rocks "were probably formed by the consolidation of fluidally-arranged heterogeneous magmas, the two ultrabasic magma fractions appearing as olivine-rich and plagioclase-rich bands, while in the basic magma the differentiation gave rise to volatile-rich and volatile-poor bands". He appended a brief description of the junction /

junction of the acid rocks with the gabbro at Harris but drew no conclusions from his description.

Dr. J. E. Richey gave a short summary of the geological literature referring to Rhum in "The Tertiary Volcanic Districts" (British Regional Geology, 1948). He suggested that the dykes of Rhum formed a radial swarm and were intersected by a series of cone-sheets.

In 1951, two years after the present writer had commenced his research on Rhum, Professor L. R. Wager and Mr. G. M. Brown published a short note on the layering of the ultrabasic rocks of Rhum. They put forward the hypothesis that the layered rocks had been built up at the base of a magma chamber partly by the upwards growth of olivine crystals and partly by the sinking of crystals from the magma above.

The present writer, in a brief note (1951) objected to Wager and Brown's hypothesis on the grounds that it did not conform to the evidence known to him. The note is included in this thesis (See below p.149). Later in the same year, he spent some time with Brown in the field with the intention of reviewing the evidence. Unfortunately, however, Brown could find neither the rock-surface shown as Plate VII in his joint paper with Wager nor the locality from which he and Wager claimed to have derived much of their evidence.

The /

The most recent published research on the Isle of Rhum comprises two papers by the present writer published in 1952. In the first paper the lavas of the west of Rhum were shown to rest unconformably upon the acid rocks, thus confirming Judd's surmise of eighty years earlier. The second paper contained a correlation of the rocks of the four volcanic outliers and a synthesis of the volcanic succession of Rhum. These two papers form part of this thesis. (See below pp. 98 - 105 and pp. 106 - 119).

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III. THE ACID ROCKS OF THE WEST OF THE ISLE OF RHUM

THE ACID ROCKS OF THE WEST OF THE ISLE OF RHUM

ABSTRACT

In the west of the Isle of Rhum Tertiary acid rocks outcrop over an area of approximately 6 square miles. Spherulitic microgranite forms the core of the acid mass and is surrounded by graphophyre. On the north the graphophyre is bounded by Torridonian Sandstone; although much of the boundary is marked by a low-angle reverse fault, part of the junction is undisturbed and a belt of transitional rocks, some 600 feet in width, intervenes between the graphophyre and the Torridonian Sandstone. The transitional rocks are divisible into five zones which are interpreted as marking successive stages in the conversion of sandstone into graphophyre. The graphophyre grades inwards into the micralso granite which is believed to represent a stage of still more advanced metasomatism.

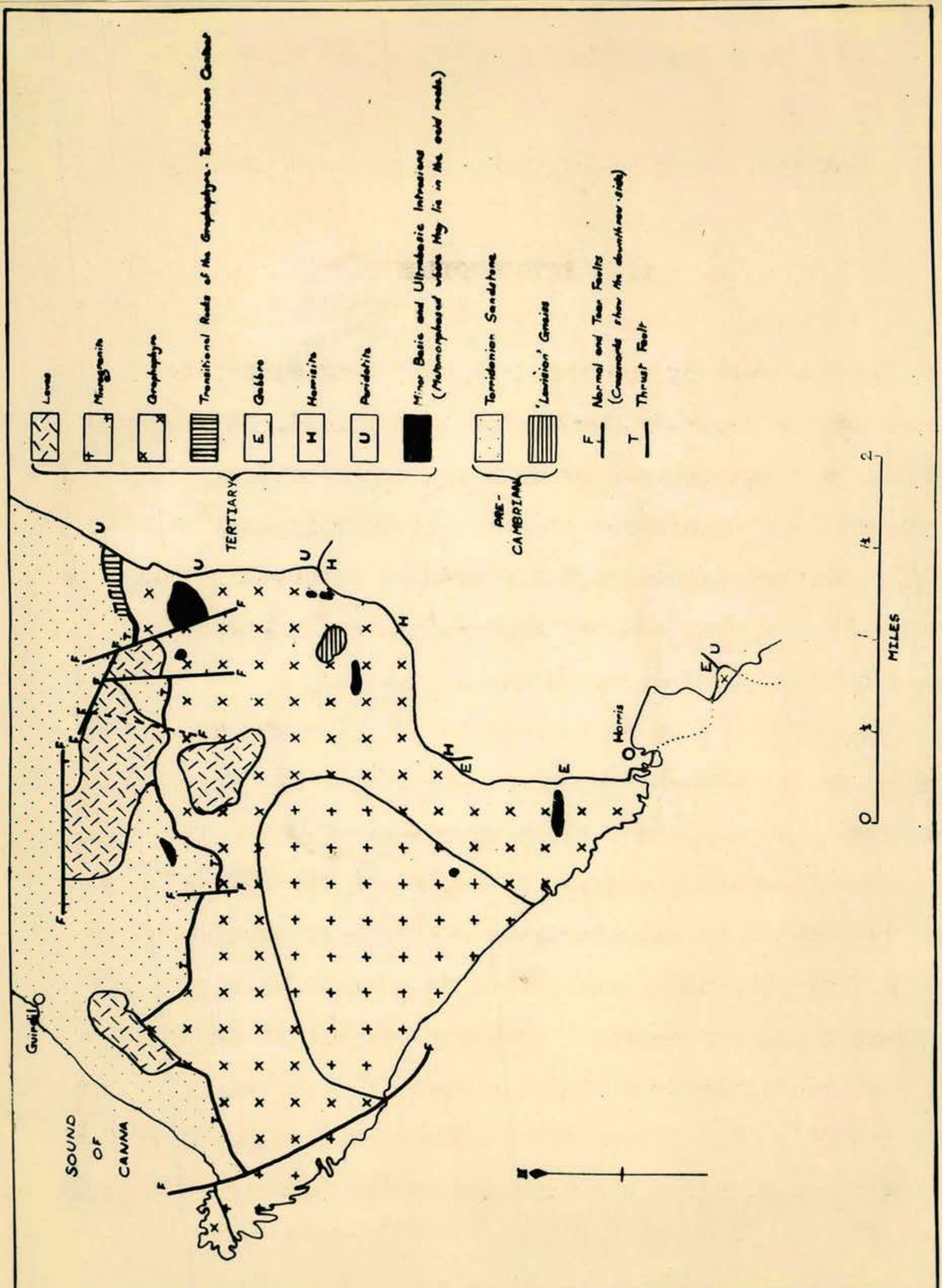

Fig. 3. Geological sketch-map of the acid rocks of western Rhum. Numerous minor intrusions have been omitted.

THE ACID ROCKS OF THE WEST OF THE ISLE OF RHUM

1. INTRODUCTION

In the west of the Isle of Rhum, acid rocks, integral parts of the Tertiary Complex of that island, outcrop over a roughly triangular area of some six square miles. They have hitherto been considered as a single petrological unit, designated granophyre, but the present author has been able to distinguish a graphophyre* towards the north and east and a spherulitic microgranite in the south-west.

The graphophyre is bounded on the north by Torridonian Sandstone, on the east by older members of the Tertiary Complex, and wherever the boundary is exposed on the south and west by the microgranite. In the north the graphophyre is partly covered by unconformable outliers of Tertiary volcanic rocks (Black, 1952, a and b) and by a small patch of the "hybrid rocks" of Harker. The area is one of moderate relief; it includes a number of well-rounded hills of which the highest is Orval, 1,869 feet above sea-level. Loose blocks of the acid rocks cover the high ground and well developed screes are /

* The term "graphophyre" (C.I.P.W., 1903) is used in preference to "granophyre" to describe one type of the acid rocks, since the latter term has been used in many previous publications as descriptive of the acid rocks as a whole.

are banked against the slopes. On the floors of the wide glaciated valleys there is usually a considerable depth of peat. Accordingly outcrops of the acid rocks are sparse and irregularly distributed, the most prominent being a broken line of crags roughly parallel to the northern boundary of the graphophyre and the sea-cliffs which in places are almost 1,000 feet high. The most conspicuous features of the tract occupied by the acid rocks are the cliff-bound outliers of Tertiary lavas and several small bodies of basic and ultra-basic rocks included in, and metamorphosed by, the acid rocks. A full investigation of these small bodies of basic and ultra-basic rocks has not yet been made but they resemble the small lenticular sills found in the nearby Torridonian rocks.

The first description of the acid rocks was given by Macculloch (1819, vol.I, p.487). Although he nowhere observed their junction with the Torridonian, he conjectured that the acid rocks were underlain by the sandstone. Judd (1874, pp. 252-253.) gave a brief account of the acid rocks and of the Torridonian Sandstone and remarked that the sandstone was metamorphosed in the neighbourhood of the granite. Geikie (1897, vol. II, p.403.), while regarding the acid rocks as intrusive, likewise failed to describe their contact with the Torridonian Sandstone.

The /

The contact was eventually mapped by Harker (1908, pp. 5-7, 102-105.) who concluded that it was "generally steep, but on the whole the granite overlies the sandstone". Harker further recorded a considerable increase in the dip of the sandstones as they are traced towards the acid rocks in the extreme west and from the sections with which he illustrated his memoir (1908, figs. 14,29, and 37.) it is clear that he was aware that the contact, steep in its eastern and central portions, dipped southwards at low angles in the west. He postulated that the acid rocks formed a laccolith intruded into the sandstone or between the sandstone and the unconformable lavas above. Bailey did not examine the acid rocks in the field but surmised (1944, p.184.) that they constitute "the filling of a subterranean cauldron-subsidence".

The present writer has demonstrated that the lavas of Orval are unconformable on the underlying graphophyre (Black, 1952, a.) thus confirming Judd's conjecture (1874, p.254.) of nearly 80 years ago. In the present study special attention is given to the internal structure of the acid mass, and to its contact relations with the Torridonian.

2. FIELD RELATIONS

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2. FIELD RELATIONS

The country rock, into which the Tertiary Complex of Rhum has been emplaced, is everywhere the Torridonian Sandstone. This formation has been divided (Bailey, 1945, p.166.) into three groups:-

Upper Arkoses and Feldspathic Grits.- 9,000 feet present, top nowhere seen.

Shales,- Over 1,400 feet thick.

Lower Grit.- Over 200 feet thick.

Bailey (loc. cit.) correlates the Lower Grit and the Shales with the Diabaig Group of the mainland Torridonian and the Upper Arkoses and Grits with the Applecross Group. In Rhum the Diabaig Group outcrops in the east and the Applecross group floors extensive areas in the west. The acid rocks of the west of the island are accordingly in contact with the arkoses and grits of this Group.

The Applecross Group in the west of Rhum consists of arkoses with pebbly grit horizons at intervals of approximately 50 feet. The rocks are red except in the neighbourhood of igneous masses where they have been bleached to a cream colour. The bleaching has been attributed to the conversion of the dispersed haematite cement to discrete grains of magnetite by Harker (1908, p.13). The regional dip of the Applecross Group /

Group is approximately 30° towards the north-west, but, where the exposures are small, accurate measurements of dip are not easily obtainable owing to the general prevalence of both slumping and current-bedding throughout the rocks of the Group. The pebbly bands are more resistant to weathering than are the arkoses, and the resulting features indicate the regional dip. Inland the Applecross Group is exposed irregularly but along the north-western coast the sea-cliffs give continuous exposures.

The graphophyre is a highly leuocratic drusy rock with phenocrysts of plagioclase and sparsely distributed small dark ferro-magnesian clots. A series of prominent platy joints with dips to the north-west at angles between 30° and 50° is intersected at right angles by two or more series of columnar joints. As the platy joints are by far the most prominent, the rock has a bedded aspect.

Like the graphophyre the microgranite is a highly leucocratic, drusy rock. It is finer in grain than the graphophyre but resembles it in containing phenocrysts of plagioclase and small dark clots of ferro-magnesian minerals. In the microgranite the columnar joints are more prominent than the platy joints, and the rock is decidedly columnar in appearance, a fact first noted by Macculloch (1819, p.487.)

In /

In hand specimen the transition from the graphophyre to the microgranite is effected by a gradual reduction in the granularity of the rock and by an increase in number and a decrease in size of the druses.

The relationship between the graphophyre and the Torridonian Sandstone is more complex. The contact between the two rocks trends approximately east and west and has a length of $4\frac{3}{4}$ miles. The contact is not well exposed; locally it lies beneath the unconformable outliers of Tertiary volcanic rocks and elsewhere it is largely concealed by scree, peat, and vegetation. However, two continuous and two discontinuous sections across the contact and numerous scattered outcrops were discovered.

The contact falls naturally into two portions. From its western extremity on the coast eastwards for a distance of some $4\frac{1}{2}$ miles, it is a plane of dislocation. Typical graphophyre and unmetamorphosed Torridonian Sandstone outcrop respectively to the south and north of the dislocation; any aureole that may have surrounded the graphophyre has been faulted out. The dislocation-plane dips southwards at 30° in the extreme west but the angle of dip steadily increases eastwards until where the dislocation is last seen the angle of dip is over 80°. Further to the east the dislocation appears to die out gradually. With increased dip of the dislocation /

dislocation, its effect on the dip of the Torridonian Sandstone decreases. In the extreme west the arkoses and grits have been highly disturbed and their dip has been increased from the regional value of 30° to almost 70°, and their strike is almost due east and west near the dislocation. Towards the east the effects of the dislocation steadily decrease until, at its eastern extremity, the Torridonian strata dip to the north-west at angles very close to the regional dip. From the disturbance induced in the Torridonian Sandstone and from the dip of the dislocation it seems clear that the dislocation is a reversed fault along which the graphophyre has been thrust northwards over the Torridonian Sandstone.

Near the easternmost point at which the fault is seen a continuous section across the fault is exposed. Normal graphophyre is separated from the Torridonian by a belt of milled rocks some 10 feet in thickness. Thin-sections show that the graphophyre near the fault is traversed by narrow shatter zones of comminuted graphophyric material, the proportion of which gradually increases as the fault is approached. Eventually a rock is encountered which contains fragments of quartz and micropegmatite embedded in a fine matrix of more finely ground material with possibly some glass. The proportion of fragments decreases and some appear to have been partly fused; /

fused; the rock is a typical mylonite. When traced towards the fault the Torridonian arkose is seen to have likewise given rise to a mylonite consisting of small quartz fragments set in a matrix of very finely ground material and possibly some glass (See Plate XXVIII, fig. 1).

The two discontinuous sections from the Torridonian to the graphophyre also cross the fault, one near the centre of its outcrop and one in the west, and although the sections are less well exposed, mylonites resembling those described above have been found in both. In neither section were rocks representing the aureole of the graphophyre found; in both places normal graphophyre has been faulted against unaltered Torridonian Sandstone. Owing to the discontinuity of these two sections the thickness of the mylonite belt could not be determined.

The age of the reverse fault can be determined within narrow limits. It has milled the graphophyre and clearly must post-date the emplacement of that rock. The lavas, lying unconformably upon both the graphophyre and the Torridonian Sandstone, have not been affected by the fault which, moreover, has itself been faulted and laterally displaced by four north-south faults, two of which cut the lavas. The reversed fault which separates the graphophyre and the Torridonian Sandstone has /

has operated after the emplacement of the graphophyre but before the eruption of the lavas and before the development of the system of block faults which traverse them.

Along the eastern part of the contact no faulting has occurred and the Torridonian Sandstone grades imperceptibly into the graphophyre through an intervening strip of transitional rocks. The contact here dips at approximately 80° towards the north.

The transitional contact is only some 400 to 500 yards in length and is not well exposed. Apart from some isolated small outcrops, the only exposure of the contact is in the continuous section presented by a somewhat broken scarp which forms the eastern face of the low hill of Minishal (ca. 1,150 feet) and some 3 miles west by north of Kinloch Castle. From a distance the cliff appears to consist of a succession of homogeneous beds with an apparent dip towards the north. On closer examination, however, it is seen that the southern part of the cliff is made up of graphophyre and the northern part of Torridonian Sandstone, the intervening part consisting of transitional rocks. The bedding planes of the arkoses and grits are continued by a series of prominent parting planes in the transitional rocks, which in turn are continued by the platy joints of the graphophyre. Moreover, the individual beds of arkose /

arkose and grit can be traced undisturbed across the transitional rocks into the corresponding 'beds' of the graphophyre. The gradation from arkose and grit into graphophyre is perfect. The southernmost arkoses, which are bleached and indurated occur some 600 feet from the northernmost outcrops of typical graphophyre and this figure is taken as the thickness of the transitional rocks. Examination of thin-sections of the rocks under the microscope, however, suggests that these bleached and indurated rocks have suffered slight metasomatism (cf. p.38).

Field investigation of the transitional rocks shows that several different types can be discriminated but, since no sharp contacts have been found between the types, it is impossible to map them separately. However, the various types can be seen to form zones roughly parallel to the belt of transitional rocks as a whole.

A prominent feature on the geological map of Rhum is the patch of "gneiss" occupying the summit of Ard Nev, a hill some 3½ miles west by south of Kinloch Castle. Unfortunately the rocks exposed on Ard Nev are so broken up by weathering that their relations cannot be determined with certainty. For this reason structural measurements are unreliable; moreover, the occurrence of harrisite boulders among these rocks suggests that /

that part of them may not be in situ. It seems that for the present the origin of these rocks must be left in doubt.

3. PETROLOGY

a. Torridonian Sandstone

The most abundant mineral of the arkoses and grits of the Applecross Group of the Torridonian Sandstone is quartz which occurs as typical, poorly rounded, detrital grains often with an undulose extinction. Feldspars, although present in a smaller proportion than quartz, are always present. The commonest feldspar is orthoclase; in addition microcline is often present and rare plagioclase also occurs. Kaolinisation and chloritisation have affected the feldspars slightly. Flakes of muscovite are sparsely distributed throughout the rocks and some detrital grains of magnetite are also present. Very occasionally there occur grains of other minerals but these make up probably less than 0.1% of the rock. The cement, small in quantity and fairly evenly distributed, is largely haematite. Argillaceous impurities are normally present in the cement and on slight metamorphism give rise to a pale green chlorite. The grain size of the arkoses varies throughout the Applecross Group but is more or less constant in individual specimens; the range of granularity is /

is from 0.25mm. to 0.75mm..

In the gritty bands small pebbles, up to 1 cm. in diameter, lie in a matrix indistinguishable from the typical arkoses. The pebbles are generally of quartzite or vein quartz.

Occasional bands and streaks rich in magnetite occur at intervals in the arkoses. However, they make up a negligible part of the total succession.

The Torridonian arkoses are bleached and indurated and have a fracture much like that of a quartzite for several hundred yards beyond the transitional rocks which mark the Torridonian-graphophyre contact (See Plate XVIII). The dispersed haematite cement has been reduced and concentrated into irregular grains of magnetite thus causing the rock to lose its red colour and to become pale cream, a phenomenon first explained by Harker (1908, p.13.). The undulose extinction of the quartz grains, so prominent in the red arkoses, is now much less conspicuous, and where quartz grains were separated one from another by small thicknesses of cement they are now immediately contiguous and commonly sutured together. This suturing together of the quartz grains probably accounts for the greater hardness and the quartzitic fracture of the indurated rocks.

B. /

b. Transitional Rocks between the Torridonian Sandstone and the Graphophyre

For convenience the transitional rocks have been divided into five parallel zones which are here lettered A to E successively from the Torridonian in the north to the graphophyre in the south. Modes of the transitional rocks could not be determined owing to their very variable composition over a single thin-section and to their fineness in grain.

Zone A.

The rocks of this zone are very similar to the bleached and indurated Torridonian Sandstone immediately to the north, but a green or greenish-brown biotite, associated with small crystals of magnetite, has been produced from the argillaceous material. The zone is approximately 100 feet thick and consists of only slightly metamorphosed Torridonian arkoses and grits. (See Plate XIX).

Zone B.

In Zone B, which is 80 feet wide, the Torridonian has been further altered. The rounded and pitted detrital grains of 'heavy minerals' and orthoclase are still preserved and the bedding is clearly traceable across the zone, but flakes of /

of brown and highly pleochroic biotite are present and increase in amount southwards. Towards the south, some of the quartz grains have recrystallised as sutured aggregates and all of them have lost the undulose extinction which is so typical of the clastic grains in the unaltered Torridonian. (See Plate XX).

The orthoclase occurs not only as cloudy and slightly sericitised detrital grains but also as clear narrow veinlets which penetrate between the quartz grains and cement them together. These veinlets increase in amount towards the south of the zone until, near the southern margin, they form a matrix in which the quartz grains are embedded. In one or two cases a particularly large crystal of the new orthoclase encloses several quartz grains, normally oriented at random, but exceptionally sharing a common optical orientation and forming a very rudimentary intergrowth with the surrounding orthoclase. This clear orthoclase is easily distinguishable from the clastic grains, and its development clearly demonstrates that K and Al have been introduced, apparently by migration along the intergranular boundaries. The source of these elements must have been in the south, for these is a gradual increase of the new orthoclase in that direction.

Zone C. /

Zone C.

Zone C is 20 feet in width. (See Plates XXI, XXII, and XXVIII Fig. 2.). Alteration of the Torridonian is now profound but the bedding retains the same dip and strike as in the unaltered Torridonian. Some detrital grains of quartz and orthoclase still occur but as in Zone B the quartz no longer has an undulose extinction. Small new crystals of orthoclase, often in rudimentary intergrowth with quartz, occur in addition to the clastic orthoclase grains. Towards the south of the zone the rocks differ markedly from those of Zone B in that the intergrowths are larger and better developed, and in that the clastic orthoclase becomes indistinguishable from the orthoclase newly formed by metasomatism.

Porphyroblasts of intensely pleochroic brown biotite occur throughout the zone and usually form chains, clusters, and poikiloblastic plates. They tend to be most abundant in the coarser parts of the rock. Equidimensional granular crystals of hypersthene and small grains of magnetite are everywhere present but are especially abundant near biotite. The proportion of ferromagnesian minerals increases southwards and the maximum for all the rocks here considered is reached at the southern margin of the zone where the rocks have beoome mesocratic. Moreover, the zone is characterised by /

by an extraordinary abundance of apatite, a mineral very rare in the Torridonian. The proportion of apatite increases southwards to reach a maximum at the centre of the zone.

No Torridonian rocks are known having compositions like those of this zone and there seems to be no escape from the conclusion that Fe, Mg, and P have been introduced and metasomatically fixed in the rocks of Zone C.

Zone D.

Zone D is 20 feet in width. In its northern part the rocks consist of a fine granular matrix of quartz, orthoclase, hypersthene, magnetite and apatite containing poikilitic porphyroblasts of biotite and sparse small pods of quartz and orthoclase which contain accessory amounts of the other minerals of the rock. (See Plate XXIII). The bedding of the Torridonian continues with unchanged dip and strike across the zone.

The quartzo-feldspathic pods, which are characteristic of Zone D, contain porphyroblasts of orthoclase enclosing numerous quartz grains and are surrounded by a basified rim in which the matrix has been enriched in biotite and hypersthene. The quartz grains enclosed in a single orthoclase porphyroblast, though often oriented at random, frequently share a common optical orientation and form a micrographic intergrowth /

intergrowth with the host orthoclase. Towards the south the pods increase in abundance and restrict the matrix to interstitial clots and irregular veins around their margins, while the proportion of intergrown orthoclase increases until, at the southern margin of the zone where the intergrowths are large, well-developed, and free from inclusion, all the orthoclase is intergrown with quartz. The presence and marked southerly increase of the pods clearly indicates that K, Al, and Si have been introduced from the south, and the concomitant development of micrographic intergrowths in the pods shows that typical micrographic textures have been produced by metamorphic and metasomatic processes.

The ferromagnesian minerals change their relative proportions from the north of the zone to the south and there is a steady southwards decrease in their total amount. Biotite, which builds large poikiloblastic crystals in the north of the zone, occurs only as small compact flakes in the south, the flakes often forming clots or clusters with a decussate structure. Hypersthene, present in considerable quantity in the north, is not found in the south of the zone, whereas hornblende, absent in the north, is the predominant ferromagnesian mineral in the south where it makes up clumps of large, subhedral or anhedral crystals associated with much magnetite /

magnetite and some biotite. Apatite resembles biotite and hypersthene in decreasing towards the s outh.

Zone E.

The rocks of this zone, 350 feet wide, contain quartz, orthoclase, plagioclase, hornblende, biotite, magnetite, and apatite. (See Plate XXIV). Intergrowths of quartz and orthoclase, similar to those of Zone D and to those of the graphophyre, make up the bulk of the rock. A few discrete crystals of quartz are present. Green hornblende is the dominant ferromagnesian mineral and is associated with abundant magnetite. Some biotite persists in the north of the zone but in the south it becomes very rare. Magnetite is common and a few prisms of apatite occur. Hypersthene, which dies out towards the s outh of Zone D, has not been found in Zone E. The southward decrease of the total proportion of ferromagnesian minerals continues across Zone E, but the rate of decrease is lower than in Zone D. As before the bedding of the Torridonian is continued undisturbed across the zone. The close resemblance of the rocks of Zone E to the metamorphosed Torridonian rocks of Zone D leads to the conclusion that the former are also the metamorphosed equivalents of the Torridonian arkoses and grits.

The /

The essential difference between the rocks of Zone E and those of Zone D is the appearance of porphyroblasts of plagioclase for the first time in the sequence. These have a composition of An_{15}* are highly sericitised, and contain inclusions of quartz, hornblende, and magnetite. The porphyroblasts increase in size and, to a lesser extent, in numbers southwards, the rate of increase being most pronounced in the northern part of the zone. They are frequently fringed by areas of micropegmatite, the orthoclase of the latter being sometimes in optical continuity with the plagioclase of the porphyroblast. Also the quartz blebs included in the porphyroblasts frequently share a common optical orientation with the quartz of one of the neighbouring intergrowths. From this it appears that the porphyroblasts have more easily replaced the orthoclase of the micropegmatite than the quartz, and accordingly they have incorporated the latter mineral as inclusions. The development of the plagioclase porphyroblasts demonstrates that Na and Ca have been added to the rocks of Zone E.

c. Graphophyre. /

* Throughout this paper the composition of the plagioclase has been determined by the symmetrical extinction angle in Albite twins.

c. Graphophyre

The graphophyre is a medium-grained leucocratic rock consisting for the most part of quartz and orthoclase with subsidiary plagioclase, hornblende, and magnetite. (See Plate XXV). Accessory minerals are rare but include apatite, epidote, and biotite. Limonite, goethite, serpentine, chlorite, and kaolin have been developed from the partial decomposition of the primary minerals.

The graphophyre closely resembles the rocks of Zone E. The micrographic intergrowths of both rocks are identical, plagioclase porphyroblasts occur in both, and the interstitial clots of hornblende in the graphophyre differ from the clots of hornblende with a little biotite in Zone E only by the suppression of the latter mineral. This continuance of characters from the metamorphosed Torridonian rocks of Zone E into the graphophyre leads to the conclusion that the graphophyre is itself a metamorphosed representative of the Torridonian Sandstone. Further evidence for this conclusion is furnished by the continuance of the bedding-planes of the Torridonian by the platy joints found throughout the graphophyre, by the absence of any contact demarcating the graphophyre from the metamorphosed Torridonian rocks of the transitional zones, by the absence of any chilled marginal phase of /

of the graphophyre, by the absence of graphophyric veins, and by the complete lack of xenoliths. It should be noted, however, that the presence of veins and xenoliths (skialiths) would not invalidate the conclusion reached.

Micrographic intergrowths of quartz and partly kaolinised orthoclase make up at least 50% of the graphophyre and in some specimens as much as 75%. In texture the intergrowths are moderately coarse and sometimes form roughly spherical masses up to several millimetres across in which the arrangement of the quartzes is approximately radial. Often, however, where the intergrowths fringe plagioclase crystals, the spherical form of the masses is only partly developed and the quartzes tend to radiate from the plagioclase. The proportions of quartz and orthoclase in the intergrowths vary but the latter mineral is always the more abundant.

Although most of the quartz is intergrown with orthoclase, some discrete anhedral quartz crystals are found. These crystals form small groups and occur between the units of intergrowth.

Plagioclase (An_{15-20}) (see footnote p.45) forms multiply twinned, slightly kaolinised crystals which are very slightly zoned. They vary greatly in size and are subhedral or anhedral, the smaller crystals tending to give rhombic sections in /

in thin slices whereas the larger crystals are more frequently irregular and are often packed with inclusions. Normally the plagioclases are fringed by several units of micrographic intergrowth (as judged by the orientation of the quartzes) but occasionally small plagioclases occur within a single unit of intergrowth. Where plagioclase is bounded by micropegmatite, indentations now occupied by intergrown quartz and orthoclase have been produced in the plagioclase which has been attacked along cleavages and twin planes, one twin member being attacked in preference to its neighbours. As a result rectangular indentations have been produced more rapidly at some parts of the crystals than at others and the boundaries of the plagioclases, where they intercept cleavages or twin planes, have castellated margins; rounding of the plagioclase crystals has never been found. On boundaries which are not intersected by cleavages or by twin planes, however, irregular indentations controlled by the cracks which traverse the plagioclase crystals have been produced. Where one of these indentations is deep enough to reach a cleavage or twin plane the margin of the indentation follows this for some distance before diverging and again becoming irregular. (See Plate XXVII, fig. 2).

The plagioclase crystals of Zone E are subhedral or euhedral /

euhedral and their margins are not indented in the above fashion and since the graphophyre has been formed from Zone E, the indentations must be due to some process which has operated in the graphophyre. The indentations are ascribed to a partial replacement of plagioclase by intergrown quartz and orthoclase, a replacement which demonstrates that K has been added to the graphophyre and that Na and Ca have been expelled probably into the rocks of Zone E where the abundance of plagioclase indicates a culmination of Na and possibly also of Ca. The very slight enrichment of the residual plagioclase of the graphophyre (An_{15-20}) (see footnote, p.45) in Ca as compared with the plagioclase of Zone E (An_{15}) suggests that the expelled material was richer in Na than was the unreplaced plagioclase of an earlier stage.

The feldspars of the graphophyre, especially the orthoclase, are markedly more kaolinised than those of any of the transitional rocks, indicating that water has been added to the graphophyre releasing K and minor amounts of Na and Ca. The released material most probably joined the migrating 'emanations'. The K was probably fixed within the graphophyre in the micropegmatite replacing the plagioclase and the Na and Ca in Zone E in the oligoclase porphyroblasts.

Magnetite is most abundant in the graphophyre, suggesting that /

that iron oxides culminate in this rock. These oxides have been driven outwards through the microgranite and have been fixed in the graphophyre.

A small proportion of hornblende is present throughout the graphophyre as short stumpy crystals which are often concentrated into small clots. The hornblende is associated with magnetite and is partly or wholly altered to chlorite or serpentine with separation of limonite or goethite. A pistacchio-green epidote is the most common accessory mineral and tends to occur in small patches. Apatite and muddy brown biotite, possibly secondary in origin, also occur in accessory amounts.

d. Transitional Rocks between the Graphophyre and the Microgranite

On approaching the microgranite the graphophyre gradually adopts characters intermediate between itself and the microgranite. The proportion of micrographic intergrowth decreases and cryptographic intergrowth appears. The corrosion effects of the plagioclase become more pronounced. The platy jointing of the graphophyre becomes less prominent and the columnar jointing increases in importance. Gradually the rocks lose their graphophyric nature and approach the mineral composition and the texture of the microgranite. Since the transition /

transition takes place over a distance of several hundred yards, the boundary between the micrograinite and the graphophyre is consequently highly indefinite and the line on Fig. 3 representing it is consequently arbitrary. In this paper rocks containing more than 50% of micrographically intergrown quartz and orthoclase are termed graphophyres and those containing less than 50% microgranites.

e. Microgranite

The microgranite is a medium-grained leucocratic rock similar in appearance to the graphophyre. It is composed largely of quartz and orthoclase, frequently intergrown, accompanied by smaller amounts of anorthoclase, plagioclase, hornblende, augite, and magnetite. The accessory minerals include epidote, apatite, zircon, scapolite, biotite, orthite, and possibly sphene; varying proportions of secondary minerals - limonite, goethite, serpentine, chlorite, and kaolin - are also present.

The microgranite is similar in many respects to the graphophyre. Both rocks are largely composed of quartz and orthoclase; hornblende occurs as small clots in association with magnetite and is the dominant ferro-magnesian mineral in both, and the plagioclase of the microgranite is almost identical /

identical with that of the graphophyre except that it has been more extensively corroded. Texturally the two rocks differ only in granularity, the microgranite being finer in grain that the graphophyre. The numerous resemblances between the two rocks and the gradual passage on the ground from one to the other suggest that the microgranite, like the graphophyre, is metamorphosed Torridonian Sandstone. This suggestion is supported by the absence of any contact or marginal phase demarcating one rock from the other by the continuation of the platy joints of the graphophyre - themselves continuations of the bedding planes of the Torridonian - into the microgranite where, although of lesser importance than the columnar joints, they are still easily observed.

The quartz of the microgranite occurs as intergrowths with orthoclase and as discrete grains the margins of which are occasionally coarsely intergrown with orthoclase, although their cores are free from that mineral. These discrete grains tend to occur along the boundaries of the intergrown quartz and orthoclase.

The orthoclase of the microgranite also occurs as intergrowths and as discrete crystals. Most frequently it forms cryptographic intergrowths with quartz, in units up to 2mm. in diameter; these intergrowths often have a spherulitic structure. /

structure. Micrographic intergrowths of the two minerals are also present and frequently form the peripheral parts of spherules of cryptographic intergrowth into which they grade. They also occur as independent masses, in which case they seldom, if ever, have a spherulitic structure; instead the quartzes are arranged in parallel rows. Large porphyroblasts of orthoclase, which are normally anhedral, rarely twinned, and crowded with inclusions of quartz, plagioclase, chlorite, magnetite, hornblende, and apatite, are of common occurrence. They have a patchy extinction and appear to consist of several parts which differ slightly from each other in optical orientation. Marginally the porphyroblasts are occasionally intergrown with quartz indicating that they have developed from quartz-orthoclase intergrowths by the increase of orthoclase and suggesting that the quartz grains which are marginally intergrown with orthoclase have developed by a similar process which has resulted in the increase of the proportion of quartz in an intergrowth. The presence of porphyroblasts of orthoclase supports the metamorphic origin of the microgranite suggested by field evidence and by similarities between microgranite and graphophyre.

Large, highly decomposed crystals of a feldspar belonging to the anorthoclase group occur in the microgranite. These crystals are normally anhedral and have a lower birefringence than /

than the other feldspars; they often show an indefinite twinning on two planes which are approximately at right angles. Optically the crystals are negative and the 2V, as estimated from the curvature of the isogyre of optic axial figures, is approximately 45°. The crystals are frequently associated with green augite and plagioclase. Harker (1904, p. 157) noted the occurrence of similar feldspar crystals in the riebeckite-granophyre of Druim-an-Eidhne and Meall Dearg in Skye. The presence of anorthoclase crystals in the micro-granite of Rhum suggests that soda has been added to the rock.

Plagiocase forms crystals of varying size throughout the microgranite. The crystals are more definitely zoned than those of the graphophyre; they have a core of about An_{25} and a slightly more sodic margin of approximately An_{20} (See foot-note p.45). Twinning is well developed although it is not conspicuous, the twin members extinguishing within 10° of one another. The crystals are turbid and partly kaolinised; they are less kaolinised than the orthoclase but contain many more inclusions of other minerals. Normally the plagioclase crystals are fringed or surrounded directly by micrographic or cryptographic intergrowths but occasionally a narrow rim of orthoclase intervenes. More extensive replacement of the plagioclase by intergrown quartz and orthoclase has occurred in /

in the microgranite than in the graphophyre and has often removed the core of a crystal while the peripheral portion, breached on one place, has been largely preserved (See Plate XXVII, fig. 1). Commonly the replacement has divided the remaining plagioclase, as seen in section, into two or more fragments each with a castellated outline and separated by intergrowth. (See Plate XXVI). The fragments of plagioclase would not fit together if the intervening intergrowth were removed, and the continuity of the twin pattern, truncated by the intergrowth, shows that movement of the fragments relative to one another has not taken place. Finally a few relict fragments of plagioclase may be left included in the intergrowth. The peripheral portion of the plagioclase is more resistent to replacement than the core and it is common to find small fragments of plagioclase in the intergrowth marking the margins of a now almost totally replaced plagioclase crystal. The larger crystals, which have irregular and poorly developed cleavages, less regular twinning, and many inclusions do not show the same regularity of outline as the smaller crystals. The replacement of much of the plagioclase by intergrown quartz and orthoclase indicates that Na and Ca have been expelled and that K has been introduced. The Na released by the replacement of the plagioclase has probably gone to help the formation of the anorthoclase of the microgranite (See /

(See above pp.53-4), and the Ca has migrated outwards to Zone E or Zone C where there are culminations in this element.

Occasionally veins of a colourless, clear, weekly birefringent mineral of a lower refractive index than the plagioclase traverse the plagioclase and possibly also the surrounding orthoclase. The mineral could not be identified with certainty but the veins seem very similar to the veins of fused plagioclase traversing the plagioclases of the Slieve Gullion granophyres described by Dr. D. L. Reynolds (1951 and 1952). Within the large plagioclase crystals there are patches, grading out into the host, with slightly abnormal extinction angles; these patches appear to be more calcic than the remainder of the crystal.

In most of the specimens examined a small proportion (5% or less), of hornblende was present. Normally it is a green variety but in some specimens bluish-green and brown types were also found. Most commonly occurring as clots of short, stumpy, subhedral crystals, it also forms long acicular crystals which are often slightly bent and occasionally occur in groups. The hornblende is partly or wholly altered to chlorite or serpentine with the separation of either limonite or goethite.

The riebeckite-granophyres of Skye are characterised by the presence of anorthoclase in addition to that of riebeckite; Harker /

Harker (1904, p.157) mentions that anorthoclase is found only in the riebeckite-bearing rocks. The acid rocks of the west of Rhum are very similar to the granophyres of Skye and one might expect that Harker's generalisation would apply to them also. However, no riebeckite has yet been found in the anorthoclase-bearing microgranite of the west of Rhum, although the occurrence of a bluish variety of hornblende suggests that some of the amphibole may be a sodic variety.

In many specimens of the microgranite a green or brownish augite has been detected. It is unevenly distributed through the specimens, being most plentiful in plagioclase-rich parts of the rock. The augite crystals form small clusters in which they are associated with grains of magnetite. The augite is partly altered to chlorite and is occasionally replaced by hornblende, the latter mineral forming a rim around a core of augite.

Magnetite is present in small amounts throughout the microgranite, as almost equidimensional grains, frequently arranged in rows, and as long slender rods. Small grains of magnetite are very commonly included in the hornblende especially in the acicular crystals; where these magnetite inclusions are very abundant the hornblende is dark green in colour.

Accessory /

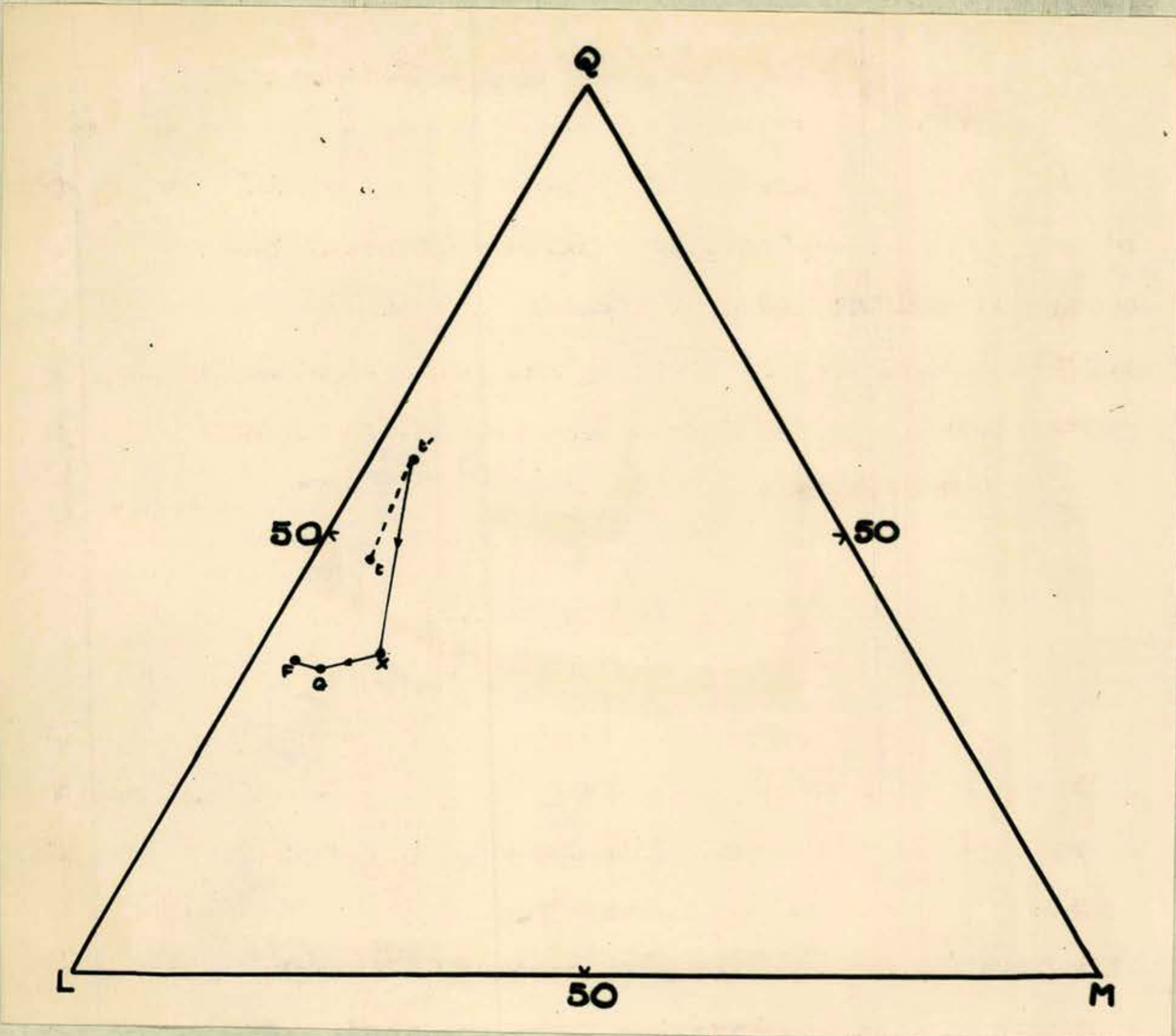

Fig. 4. Von Wolff diagram illustrating the chemical transformation of Torridonian Sandstone to Tertiary microgranite.

t Torridonian Sandstone (A, Table 1).
t' Bleached and indurated Torridonian Sandstone (I, Table 1).
X Transitional rock from Zone C (II, Table I).
G Graphophyre (III, Table 1).
F Microgranite (IV, Table 1).

Accessory minerals are present in great variety in the micrografite but together they make up a very small proportion of the rock. They include a pistacchio-green epidote which occurs in patches and small druses, zircon, apatite, scapolite, replacing plagioclase, orthite, and small crystals of pleochroic brown biotite. Some very small, irregular crystals suggestive of sphene were noted.

4. PETROCHEMISTRY

No chemical analyses of rocks from the west of Rhum have hitherto been recorded. Harker, for whom most of the published analyses of rocks from Rhum were made, stated that the acid rocks of the west of the island "have nothing to distinguish them from the corresponding rocks of Skye" (1908, p.102) and consequently did not have the rocks analysed. The present writer has had four analyses made of the rocks from the west of Rhum. One of these represents a composite sample of the bleached and indurated Torridonian Sandstone (I, Table 1) which lies immediately to the north of the transitional zone. The others were made from typical specimens of a transitional rock from Zone C(II), the graphophyre (III), and the micro-granite (IV).

From /

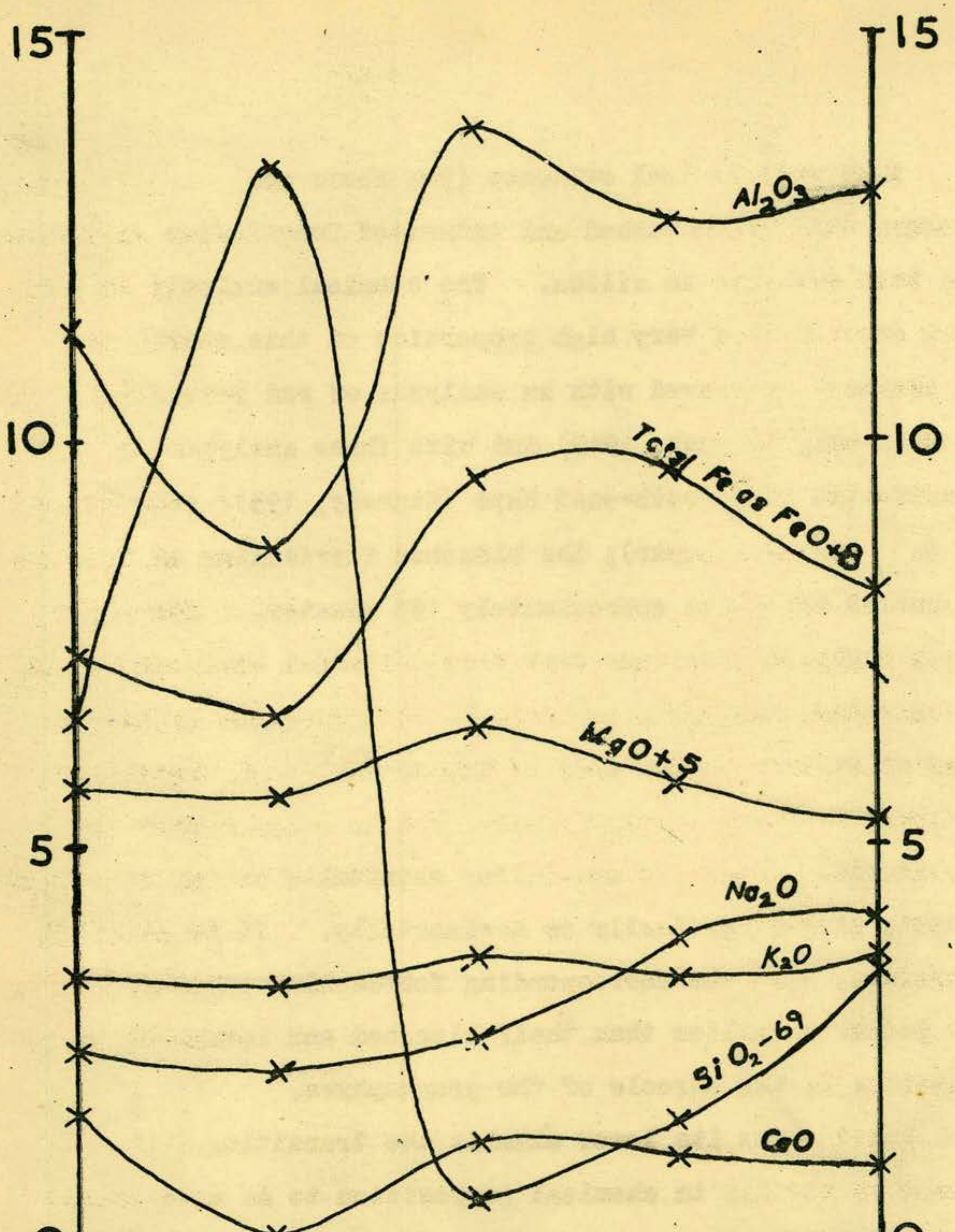

Fig. 5. Variation diagram illustrating the chemical tran formation of Torridonian Sandstone to Tertiary micro- granite. A, I, II, III and IV have the same signifi cance as in Table 1, p. 71.

From petrological evidence (See above ~~pp~~p.38) it appears that the bleached and indurated Torridonian Sandstone has been enriched in silica. The chemical analysis of this rock shows that a very high proportion of this constituent is present; compared with an analysis of red Torridonian grit from Glenelg (Clough, 1910) and with three analyses of Torridonian from south-east Skye (Kennedy, 1951) (See Table 1 on p. 71 of this paper), the bleached Torridonian of Rhum has a content of silica approxiamtely 15% greater. Kennedy's three analysed specimens come from different horizons in the Torridonian; Clough's analysis is of a specimen collected some miles away to the east of Kennedy's. All these four analyses are very closely similar and it appears that the Torridonian arkoses do not differ chemically to any considerable extent, either vertically or horizontally. It is probable, therefore, that the corresponding Torridonian arkoses of Rhum are poorer in silica than their bleached and indurated representatives in the aureole of the graphophyre.

Apart from its lower alkalis the transition rock from Zone C is similar in chemical composition to an acid craignurite from the Glen More Ring-dyke of Mull (Cf. II and B Table 1). In mineral composition, however, the two rocks are widely different.

From /

From petrographic evidence it has been determined that the rocks of Zone C have been formed by two petrographically distinct stages of metasomatism from the bleached and indurated Torridonian Sandstone. The first stage, in which the rocks of Zone B were formed, was characterised by enrichment of these rocks in K and Al; the second stage by enrichment in Fe, Mg, and P. The total result of these two stages of metasomatism can be ascertained chemically by comparing analyses I and II when it is found that Zone C has been enriched not only in K, Al, Fe, Mg, and P but also, to a lesser extent, in Na, Ca, Ti, and Mn.

The graphophyre belongs to the less acid group of the British Tertiary granites and granophyres and most closely resembles the Red Hills granophyre of Skye (Harker, 1904, p.153), (Cf. III and C, Table 1), though it should be noted that it contains considerably less K_2O. Indeed, in the Rhum graphophyre K_2O is less than Na_2O - a relation which is uncommon in the Tertiary granites and granophyres of the British Isles.

From petrographic evidence it is known that the graphophyre has been metasomatically produced from the rocks of Zone C; also it has been petrographically determined that this metasomatism took place in three distinct stages. The first of these stages represented by Zone D was characterised by addition of K_2O, CaO, and SiO_2 and subtraction of MgO; in the /

the second stage (represented by Zone E) Na_2O, and to a less extent, CaO were added and K_2O subtracted; the third stage (represented by the graphophyre itself) involved slight addition of K_2O and SiO_2 and subtraction of CaO. In the case of a few constituents the various successive enrichments and impoverishments counteracted one another; potash, for example, became enriched in the first stage, impoverished in the second, and slightly enriched again in the third, the net effect being an impoverishment, as shown below.

The total algebraic effect can be determined chemically by a comparison of the analyses II and III (Table 1). It is found that the graphophyre has been enriched in Na_2O, Fe_2O_3 and SiO_2, and has been impoverished in K_2O, CaO, MgO, Al_2O_3 and TiO_2 as compared with the rocks of Zone C.

The microgranite, like the graphophyre, belongs to the group of less acid British Tertiary granites and granophyres. It closely resembles an analysed specimen of granophyre from 750 yards to the south-east of Dunan in the Isle of Skye (Cf. IV and D, Table 1). The microgranite, however, differs from this rock in that, like the graphophyre, it contains more soda than potash.

From petrographic evidence it has been determined that the microgranite could be regarded as having been formed from the /

the graphophyre by the introduction of K_2O and SiO_2, and possibly also a little Na_2O, together with some expulsion of iron oxides and, to a less extent, of CaO. These conclusions are borne out by a comparison of analyses III and IV (Table 1). The chemical data also demonstrate that the microgranite (IV) has been slightly enriched in Al_2O_3 and slightly impoverished in in MgC, TiO_2 and P_2O_5.

The metasomatism which has produced the microgranite from Torridonian Sandstone has altered the chemical composition of the latter chiefly by enriching it in Al_2O_3, Na_2O, FeO, Fe_2O_3, CaO and K_2O. Minor constituents - TiO_2, MnO and P_2O_5 - have also been added. The source of these constituents has not been traced and it can only be postulated that they have been introduced into the Torridonian Sandstone from depth.

The red Torridonian of Rhum is very probably closely comparable in chemical composition to Kennedy's analysed specimens from south-east Skye. Consequently the bulk of the material expelled from the Torridonian by the metasomatism was SiO_2. The mode of disposal of this excess SiO_2 must now be determined.

The bleached and indurated Torridonian rocks of Rhum appear from petrographic evidence to have suffered silicification. A comparison of analyses A and I also shows that the bleached and indurated rocks are significantly more silicic than /

than the normal red arkoses. The source of the SiO_2 which has been introduced into the bleached and indurated rocks presumably lay to the south; the silica expelled from the acid and transitional rocks by the metasomatism has been driven outwards and is now lodged in the bleached and indurated Torridonian where it culminates and forms an 'acid fromt'.

A comparison of analyses A and I also shows that the bleached and indurated Torridonian rocks are poorer in Al_2O_3, FeO and Fe_2O_3 than the normal Torridonian. The differences in the content of iron oxides of the two rocks can be explained by a slight difference in their contents of detrital magnetite and chlorite. The excess Al_2O_3 present in the Torridonian rocks from Skye as compared with the bleached and indurated Torridonian of Rhum is possibly due to the presence in the former of a larger proportion of argillaceous material or of sericite. There is no evidence available to show that the excess Al_2O_3 has been driven outwards from the bleached and indurated Torridonian to form a separate 'front' further to the north.

Culminations and depressions of various constituents are present in the acid and transitional rocks of the west of Rhum (See figs. 4 and 5). The chemical analyses show culminations /

tions of Al_2O_3, FeO, TiO_2, CaO, MgO and MnO in the rocks of Zone C, and culminations of Fe_2O_3 and P_2O_5 in the graphophyre.. A slight depression in SiO_2 and a secondary culmination in K_2O occur in the rocks of Zone C.

The geochemical changes which have affected the Torridonian rocks of the west of Rhum agree with the conclusion reached by Dr. D. L. Reynolds (1946) after a study of the geochemical data from some thirty areas where metasomatism has taken place. She wrote (p.434) "when granite ...... is emplaced ..... its emplacement involves an ... enrichment of an adjoining zone of the neighbouring rock in alkalis, one or more of the cafemic constituents, and one or more of the minor constituents TiO_2, P_2O_5 and MnO, some or all of which show geochemical culmination." In the west of Rhum the rocks adjoining the acid rocks have been enriched in alkalis, in all three cafemic constituents, and in all three minor constituents.

The various types of metasomatised rock from concentric sheels about a centre located in the sea 2 miles west by north of Harris Lodge. If it is assumed that the volume enclosed by the outer limit of each shell varies with the cube of the distance from the centre to the outer limit of the shell, values proportional to the volume of each of the metasomatic /

matic rocks can be calculated.

The outer limit of the microgranite is 4,000 yards from the centre. The volume of the microgranite is therefore proportional to 64. The outer limit of the graphophyre is 6,600 yards from the centre. The volume enclosed by this limit is proportional to 287, of which 64 is microgranite. The volume of the graphophyre is therefore proportional to 223. Similarly the transitional rocks, whose outer limit is 6,900 yards from the centre have a volume proportional to 41, and the silicified Torridonian, the outer limit of which is 7,300 yards from the centre, has a volume proportional to 61. The volume of the entire metasomatised mass is proportional to 389. Now, the average specific gravity of the microgranite is 2.50, of the graphophyre 2.60, of the transitional rocks 2.70, and of the silicified Torridonian 2.60; therefore the weights of each type of rock present are approximately proportional to 160, 580, 137, and 159, respectively.

The quantity of any oxide in any of the four rocks is proportional to the product of the percentage of the oxide given in the appropriate analysis (Table 1) and the weight of the rock. The total quantity present in the metasomatised mass is proportional to the sum of the quantities present in the /

the four metasomatised rocks. The values relating to seven oxides are set out in Column X, Table 4.

The average specific gravity of the unaltered Torridonian is 2.47 and the weight of this rock which occupied the space now occupied by the metasomatised rocks is proportional to approximately 961. The quantity of any oxide in this weight of unaltered Torridonian is proportional to the product of the percentage of the oxide present (as given in analysis A, Table 1) and 961. The values relating to seven oxides are set out in Column Y, Table. 4.

The effects of metasomatism are shown by the differences between the values for the seven oxides in Column X and in Column Y. These differences show that Na_2O, Al_2O_3, iron oxides and MgO have been added to the Torridonian during the formation of the metasomatised rocks. Little, if any, change has taken place in the quantities of SiO_2, CaO, and K_2O present.

5. CONCLUSIONS

The microgranite, graphophyre, and transitional rocks between the latter and the Torridonian Sandstone have been produced by metasomatism and metamorphism of the Torridonian Sandstone. The processes concerned occurred while the rocks remained /

remained essentially in a solid state; the process of conversion of the Torridonian to microgranite can be regarded as having taken place in a continuous series of stages, of which it has proved practical to recognise six. The metasomatism has enriched the Torridonian rocks in Al_2O_3, Na_2O, FeO, Fe_2O_3, CaO, and K_2O; these constituents are postulated to have been introduced into the rocks from some source in depth. SiO_2 was the main constituent expelled from the Torridonian; it is suggested that the expelled SiO_2 was mainly disposed of in the acid front represented by the bleached and indurated zone of the Torridonian.

The granophyres of metsomatic origin described by Dr. Reynolds (1951) from Slieve Gullion in north-eastern Ireland differ from the acid rocks of the west of Rhum in that they have been formed from rhyolite lava flows and from tuffs which in turn have been derived from the Newry granodiorite. They also differ from the Rhum rocks in that they form layers in a gabbro-granophyre complex and also highly transgressive masses. The acid rocks of the west of Rhum, on the other hand, form a relatively large, boss-like mass.

The main conclusion of the present paper, namely that the acid rocks of the west of Rhum are the metamorphosed representatives of the Torridonian Sandstone, is the same as that /

that reached by King (1953) as to the origin of the granophyres of the Creag Strollamus area in Skye. The contact phenonoma found between the granophyre and Torridonian in Skye have been described by King and seem to be almost identical with those found between the graphophyre and Torridonian in the west of Rhum. In both Skye and Rhum the conclusion that the acid rocks are metasomatised Torridonian has been drawn from both structural and petrological evidence.

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TABLE 1.

	A	I	II	B	III	C	IV	D	E
SiO_2	75.58	82.44	69.57	68.12	70.55	70.34	72.54	73.52	72.78
Al_2O_3	11.39	8.68	13.79	13.08	12.68	13.18	13.03	13.38	-
Fe_2O_3	0.82	0.64	1.37	1.02	2.94	2.65	1.96	1.13	-
FeO	1.63	1.05	3.35	3.26	2.09	2.24	1.39	1.68	-
MgO	0.73	0.64	1,49	0.71	0.78	0.40	0.32	0.15	-
CaO	1.69	0.15	1.43	1.81	1.12	1.24	0.97	0.92	-
Na_2O	2.46	2.28	2.66	4.15	3.92	3.61	4.04	3.87	4.08
K_2O	3.35	3.27	3.67	4.47	3.36	4.90	3.68	4.80	5.18
$H_2O+105°C$	1.07	0.56	0.88	1.16	1.28	0.76	0.90	0.39	-
$H_2O-105°C$	0.05	0.16	0.47	0.40	0.53	0.46	0.43	0.31	0.34
CO_2	0.51	nil	nil	0.06	nil	-	nil	0.18	-
TiO_2	0.42	0.26	0.87	1.26	0.78	0.46	0.42	0.22	-
P_2O_5	0.30	trace	0.12	0.22	0.13	0.10	0.03	0.05	-
MnO	0.05	0.04	0.09	0.39	0.07	0.19	0.06	0.08	-
FeS_2	-	-	-	-	-	-	-	0.08	-
(Ni,Co)O	-	-	-	0.00	-	-	-	-	-
BaO	-	-	-	0.00	-	0.00?	-	-	-
Li_2O	-	-	-	0.00	-	0.00?	-	-	0.00
	100,05	100.17	99.76	100.15	100.23	100.55	99.77	100.76	-

TABLE 1.

A	Average of Kennedy's analyses A(1), A(2), and A(3) of the Torridonian arkoses from south-eastern Skye. (Kennedy, 1951, P. 258).
I	Composite sample of bleached and indurated Torridonian arkose from the outer part of the aureole of the graphophyre in the west of Rhum. Analyst: W. H. Herdsman.
II	Transitional rock between the Torridonian and the graphophyre, Zone C, 2,800 yards east-north-east of the summit of Orval, Isle of Rhum. Analyst: W. H. Herdsman.
B	Craignurite (acid). Glen More Ring-dyke, 130 yards east-south-east of cairn on Cruach Choireadail, Mull. Analyst: E. G. Radley. (Bailey, Richey, et. al., 1924, p. 29).
III	Graphophyre, 800 yards east of the summit of Orval, Isle of Rhum. Analyst: W. H. Herdsman.
C	Hornblende-granophyre. Red Hills main mass. South end of Druim Eadar Da' Choire, west side of Coire na Seilg, Skye. Analyst: W. Pollard. (Harker, 1904, pp. 153, 216).
IV	Microgranite, 2,400 yards south-west of the summit of Orval, Isle of Rhum. Analyst: W. H. Herdsman.
D	Granophyre, 700 yards south-east of Dunan, Isle of Skye. Analyst: T. C. Day. (Day, 1931, p. 58, analysis S.1.)
E	Riebeckite-granophyre, between Meall Dearg and Druim na Eidhne, Skye. Analyst: W. Pollard. (Harker, 1904, p. 153.).

TABLE 2.

NORMS

	A	I	II	III	IV
Quartz	45.22	54.90	33.38	31.60	32.35
Orthoclase	19.81	19.31	21.70	19.87	21.76
Albite	20.82	19.29	22.50	33.14	34.18
Anorthite	3.17	0.75	6.40	4.73	4.62
Corundum	2.55	1.12	3.10	0.87	0.70
(Fe	1.72	1.05	3.71	0.25	0.34
Hypersthene	3.54	2.65	7.44	2.21	1.13
(Mg	1.82	1.60	3.73	1.96	0.79
Magnetite	1.18	0.93	1.99	4.26	2.85
Ilmenite	0.80	0.51	1.66	1.49	0.80
Apatite	0.71	trace	0.28	0.30	0.07
Calcite	1.16	....	....	....	....
Water	1.12	0.72	1.35	1.81	1.33
	100.08	100.18	99.80	100.28	99.79

Note :- A, I, II, III, IV have the same significance as in Table 1.

TABLE 3.

VON WULFF VALUES

	A	I	II	III	IV
Q	46.92	58.22	36.61	34.80	35.74
L	47.66	37.82	52.13	58.57	60.53
M	5.42	3.96	11.26	6.62	3.74

TABLE 4

	X	Y	Change*	%Change*
SiO_2	73,295	72,650	+645	+0.9
Al_2O_3	12,291	10,730	+1,561	+14.5
Total Fe as FeO	4,016	2,275	+1,741	+76.4
CaO[t]	988	997[t]	-9	-0.1
MgO	824	701	+ 123	+17.6
Na_2O	3,572	2,362	+1,210	+51.2
K_2O	3,465	3,218	+ 247	+7.7

* Where the oxide has been metasomatically added the change is shown as posśtive; where it has been subtracted the change is shown as negative.

t Sufficient CaO to combine with the CO_2 has been subtracted from Analysis A before obtaining the value quoted. The unaltered Torridonian of Rhum is not known to contain calcite.

A TERTIARY VENT IN THE EAST OF THE ISLE OF RHUM

ABSTRACT

A small Tertiary vent, situated in the east of the Isle of Rhum approximately 3¼ miles south of Kinloch Castle, is described. It lies on a ring-fault which separates Tertiary gabbro to the north-west from Torridonian Sandstone to the south-east; the vent is filled with rocks varying in composition from microgranite in the south-east, through marscoite in the centre, to quartz-gabbro in the north-west. These rocks are shown to be highly metamorphosed pyroclastic rocks consisting of fragments which have been derived from the walls of the vent. The gases passing up the vent are estimated to have attained a temperature in excess of 1,000°C and were charged with H_2O and compounds of K, Na, Ca, Al, Si, and P; the vent rocks have been enriched in these constituents.

The Torridonian rocks immediately contiguous to the vent have been enriched in K, Na, Ca, Al, Fe, Mg, P, and H_2O at the expense of Si. This metasomatism is believed to have occurred at temperatures ranging from 870°C to over 1,000°C. Beyond the zone of metasomatism the Torridonian has been recrystallised for some distance from the vent at temperatures which seem to have ranged from 600°C to over 870°C. Quartz veinlets, believed to have originated in the metasomatic zone, traverse the recrystallised Torridonian Sandstone.

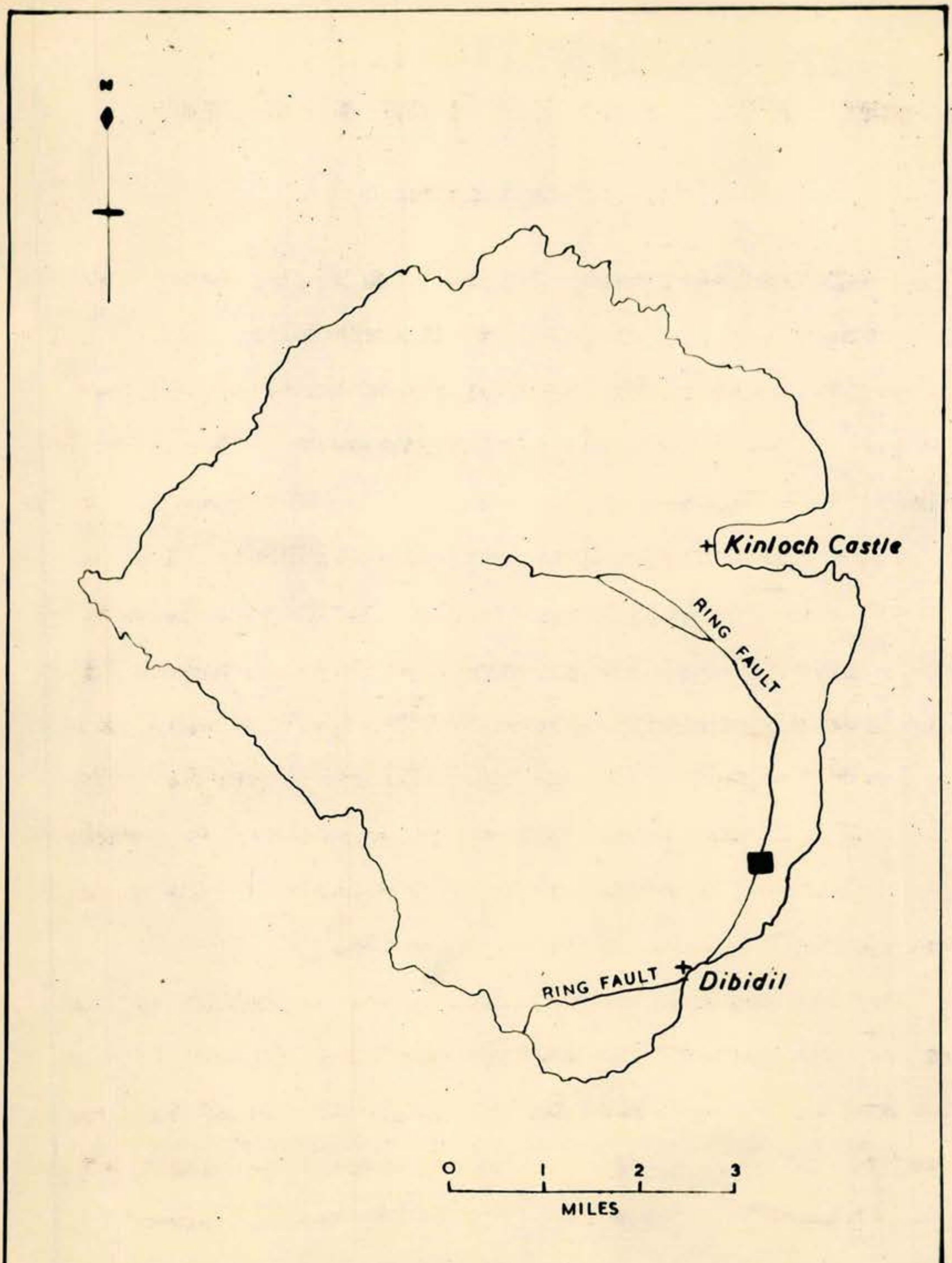

Fig. 6. Sketch-map showing the locality of the Tertiary vent (black rectangle) in the east of Rhum.

A TERTIARY VENT IN THE EAST OF THE ISLE OF RHUM

1. INTRODUCTION

A small Tertiary vent, filled with highly metamorphosed pyroclastic rocks, is situated on the northern slopes of the valley of the Allt na Ba about 1½ miles north-north-east of the ruined house at Dibidil and approximately 3¼ miles south of Kinloch Castle (see Figs. 6 and 7). The outcrop of the vent is elongated from north-east to south-west; its maximum length is approximately 70 yards and its breadth is some 25 yards. The vent and its metamorphic aureole have not previously been described. Harker (1950, p.68) described and figured metamorphosed arkoses in which micrographic intergrowth and quartz pseudomorphs after tridymite are developed and which closely resemble some of the rocks in the aureole of the vent but gave no precise locality.

The vent and the Torridonian strata which lie within the south-eastern part of its aureole are well exposed in a series of roches moutonnées and also in the gorge of one of the tributary streams of the Allt na Ba. The north-western margin of the vent is obscured by peat and vegetation and its aureole in this direction is not exposed. Gabbro outcrops a short distance to the west of the vent and it is probable that the north-western wall of the vent consists of altered basic rocks.

The vent occurs on a ring-fault (Bailey, 1944) which, in this /

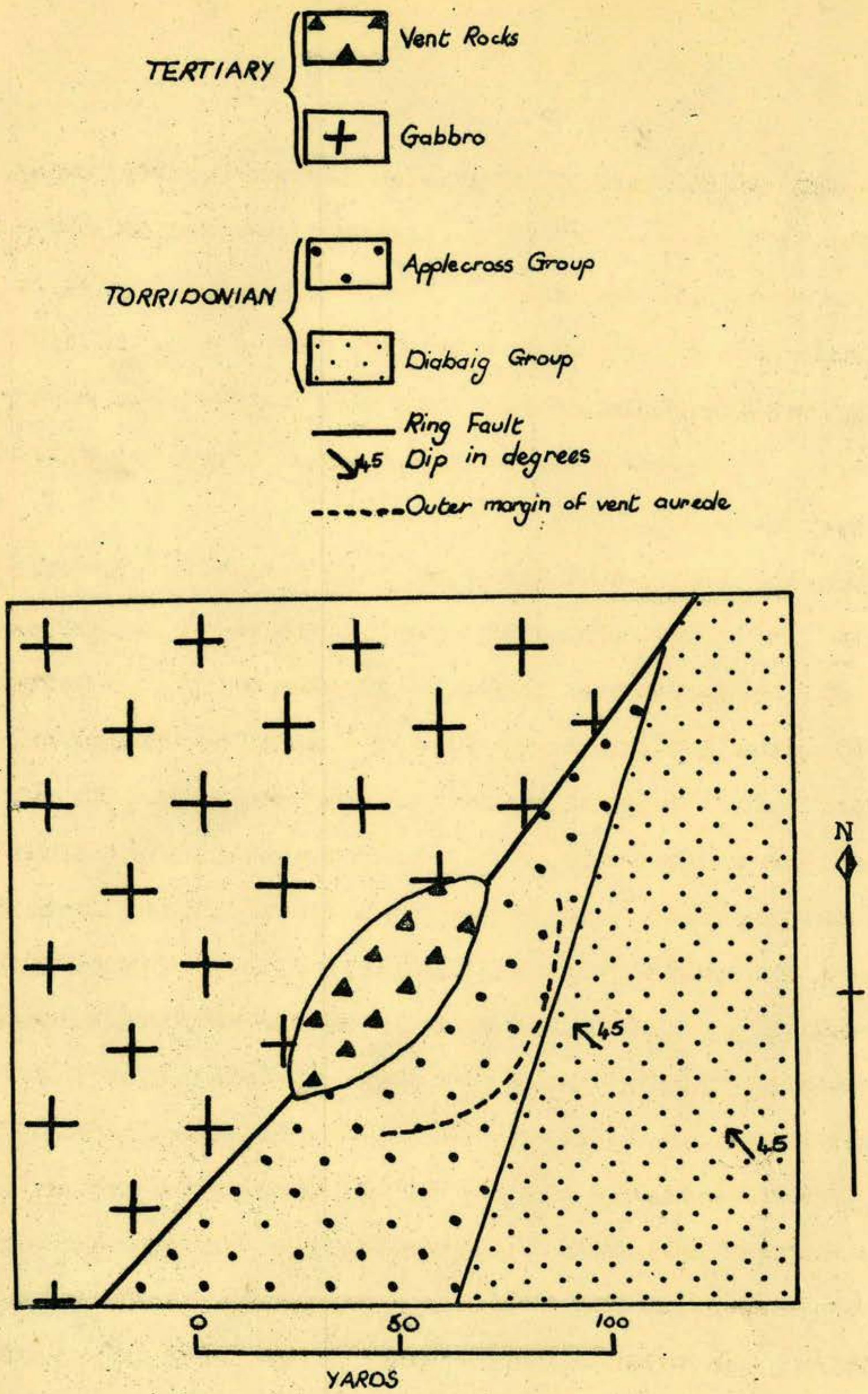

Fig. 7. Geological sketch-map of the Tertiary vent.

this part of the island, separates the peripheral gabbro of the Tertiary complex of Rhum from the Torridonian country-rock to the south and east. The Torridonian strata in the neighbourhood of the vent have been much disturbed by the fault, but the rocks of the vent have suffered no such disturbance; they were therefore emplaced after the cessation of fault movement.

On the south east the vent is margined by Torridonian arkoses and grits belonging stratigraphically to the basal part of the Applecross Group. Siltstones of the dominantly argillaceous Diabaig Group underlie these rocks and outcrop approximately 30 yards to the east of the vent a few yards beyond the outer limit of the vent aureole. The siltstones are quartzo-feldspathic in composition and differ from the arkoses and grits only in granularity. All the sediments exposed at present in the aureole of the vent were originally quartzo-feldspathic rocks and their division into two stratigraphical groups is irrelevant to the purpose of this paper.

The metamorphic aureole of the peripheral gabbro of the Rhum complex extends for a considerable distance to the east of the ring-fault and includes the aureole of the vent. As a result, the metamorphism caused by the vent is superimposed upon that caused by the gabbro. Fortunately the relatively slight metamorphism produced by the gabbro is of little importance /

importance in comparison with the intense local metamorphism associated with the vent.

2. PETROLOGY

I. Torridonian Sandstone

The Torridonian Sandstone outside the vent aureole is made up of almost black siltstones which have been slightly metamorphosed by the gabbro to the west. The siltstones have a general westerly dip at angles approximating to 45°, but are highly contorted on a small scale. Differential weathering has picked out the finer beds and left the coarser outstanding, thus rendering the contortions of the bedding planes very conspicuous.

Poorly rounded quartz grains predominate in these rocks and are accompanied by considerable amounts of orthoclase. Iron ores and chlorite occur throughout and are locally very abundant in small lenticles. Highly pleochroic brown biotite is common, particularly in the chloritic lenticles. Detrital grains of heavy minerals, of which the commonest is apatite, are sparsely distributed throughout the rocks.

II. Metamorphosed Torridonian Sandstone of the Vent Aureole

The Torridonian Sandstone forms the south-eastern part of the vent aureole which is here about 25 yards in width. Two /

Two zones of approximately equal width are present, the outer consisting of recrystallised, and the inner of metasomatised, Torridonian. No sharp contact has been observed and there appears to be a perfect transition from the country-rock through the aureole rocks into the rocks of the vent.

a. Recrystallised Torridonian

This zone is made up of bluish-black rocks which lose their bedding as they are traced inwards. The rocks have been partly or wholly recrystallised by the metamorphism of the vent, and the degree of recrystallisation increases north-westwards.

Quartz predominates and is accompanied by a considerable amount of orthoclase. Both minerals occur as poorly rounded grains in the south-eastern part of the zone but become mutually intergrown to an increasing extent towards the north-west until in the extreme north-west the detrital grains have been completely replaced by recrystallised aggregates and intergrowths. The intergrowths are present in all stages of development and can be seen to have formed only where quartz and orthoclase grains were contiguous. Where no orthoclase was present the quartz has recrystallised into sutured aggregates; where the orthoclase was relatively deficient in amount the intergrowths have cores of quartz. Slender, lath-shaped /

shaped pseudomorphs of quartz after tridymite are seen in sections cut from specimens from the north-western part of the zone showing that the temperature of the rocks during recrystallisation probably exceed 870°C.

Biotite is present in association with magnetite. Small crystals of pale hypersthene are frequent especially in magnetite-rich parts of the rock. Aggregates of pale brown chlorite are common and sparse grains of heavy minerals other than magnetite occur. Accessory amounts of newly crystallised apatite are present throughout the rock and suggest that the materials introduced contained a little phosphorus.

The rocks are traversed by light-coloured veinlets consisting of quartz, subsidiary amounts of pale green chlorite, and a little euhedral apatite. Near the veinlets chlorite is abundant and the orthoclase is unusually turbid: facts which suggest that water was introduced into the recrystallised rocks along the veinlets.

b. Metasomatised Torridonian

The rocks of the south-eastern part of this zone very closely resemble the recrystallised Torridonian but the resemblance decreases towards the north-west where the rocks approach fine-grained granophyres in appearance and texture. Quartz is the commonest mineral in the metasomatised rocks, where /

where it occurs as intergrowths with orthoclase, as pseudomorphs after tridymite, and as sutured aggregates of discrete grains. The proportion of quartz pseudomorphs after tridymite steadily increases towards the north-west. Orthoclase is common, both as intergrowths with quartz and as large porphyroblasts which include all the other minerals present. The orthoclase is everywhere turbid and has been converted locally to green chlorite. Plagioclase is lacking in the extreme south-east of the zone but occurs in the central and north-western parts. Where it first appears it forms large poikilitic, in addition to subhedral or euhedral, porphyroblasts but the poikilitic crystals disappear further towards the north-west where only subhedral or euhedral crystals occur. The plagioclase increases in amount north-westwards; in the extreme north-western part of the zone it is abundant and has suffered slight corrosion along the cleavages.

Flakes of biotite and small grains of pale hypersthene are common and poikiloblasts of these two minerals also occur. Biotite flakes are included along the cleavages of the plagioclase forming a crude type of intergrowth. In the north-west of the zone prismatic crystals of green hornblende appear for the first time. Small grains of magnetite and prisms of apatite are abundant throughout the zone.

The /

The exceedingly variable composition of the rocks of this zone (on a micro-scale) makes it difficult to determine accurate modes, but it is visibly apparent that the rocks are richer in feldspars, ferromagnesian minerals, magnetite, and apatite than the recrystallised sediments of the outer zone. In view of the occurrence of poikilitic porphyroblasts of orthoclase, plagioclase, biotite, and hypersthene and the increased proportions of magnetite and apatite, it seems likely that K, Na, Ca, Al, Fe, Mg, P, and H_2O have been added to the rocks of this zone at the expense of, mainly, Si. The proportions of the feldspars and the ferromagnesian minerals vary considerably throughout the zones and there does not seem to be any well defined succession of 'fronts'.

III. Rocks of the Vent

The rocks which occur within the vent are mixtures of mechanically derived fragments of acidic and basic material. In the extreme south-east of the vent most of the rocks resemble the metasomatised Torridonian from which - or from the ancestral material of which - they have been largely derived; only a very small proportion of basic material is present. The rocks in the centre of the vent contain acidic and basic fragments in approxiamtely equal proportions; the rocks of the north-western part of the vent are largely made up of the basic material derived from /

from the gabbroic north-western wall of the vent. Apart from the pyroclastic fragments, material brought up by the gases in the vent (see p.94) is also present.

The rocks of the vent will be described from south-east to north-west - that is from the most acidic to the most basic.

a. Acid Rocks

The acid rocks of the vent consist for the most part of quartz, orthoclase, plagioclase, augite and hornblende and resemble microgranite. Fragments of basic rocks lie in acidic material containing a small admixture of comminuted basic material. Acidic fragments cannot be individually distinguished.

The augite of the basic fragments is almost totally altered to a brownish chlorite. It is associated with plagioclase (An_{50}), the crystals of which are almost unzoned where they are in contact with the augite but highly zoned where they adjoin the matrix, the outer rims having a composition of An_{30}. The calcic cores are sharply demarcated from the more sodic rims. Fragments of plagioclase showing similar pecularities of composition but the patches of brownish chlorite in place of augite are found in the dominantly acidic portions of the rock. These crystals and aggregates have /

have undoubtedly been derived from the basic rocks. The basic xenoliths and xenocrysts are present in very small amounts in the extreme south-east of the vent but the proportion steadily increases north-westwards.

The acidic parts of these rocks probably comprise both fragments and detached crystals. Quartz is present as intergrowths with orthoclase and as sutured aggregates. It also forms discrete crystals and, rarely, pseudomorphs after tridymite. Considerable amounts of turbid orthoclase are present, generally in the form of intergrowths with quartz. Plagioclase occurs as numerous, multiply twinned, zoned crystals. The cores of the plagioclase crystals have a composition of An_{35} and are sharply separated from the outer parts of the crystals which have a composition of An_{30}. Concentric bands of abnormally turbid plagioclase are found in some crystals while in others the zoning has been truncated suggesting that the crystals have been broken. The crystals are frequently surrounded by intergrowths of quartz and orthoclase, and this, taken in conjunction with their composition, serves to distinguish them from plagioclases derived from the gabbro. As in the Metasomatised Torridonian the plagioclase crystals in the acidic part of the acid vent rocks are often slightly corroded, the corrosion having followed the cleavages of the crystals. Hornblende occurs as prismatic /

prismatic crystals; biotite is uncommon; small amounts of pale hypersthene are present. Magnetite, in grains of varied sizes, and apatite occur in accessory amounts.

A noteworthy feature of the plagioclase crystals of the acid vent rocks is the presence of veinlets of colourless material traversing the calcic cores but not the sodic margins. The material in the veinlets has a lower refractive index than the host plagioclase and is normally isotropic. Occasionally, however, it is feebly birefringent. These veinlets seem to be identical with the veinlets of fused plagioclase found in the plagioclase crystals of various transgressive rocks masses on Slieve Gullion by Dr. Reynolds (1951 and 1952).

b. Intermediate Rocks

These rocks are coarse-grained and mesocratic and have a gabbroic aspect in the north-west of the zone. They consist of acidic and basic fragments set in a fine-grained matrix, and appear to be typical marscoites.

The acidic fragments consist of quartz and highly turbid orthoclase. The basic fragments are more distinct and comprise partly decomposed plagioclase with cores of composition An_{50} surrounded by rims of An_{30}, and pale coloured augite, occasionally sub-ophitic, which has been largely decomposed to /

to chlorite with the separation of magnetite and possibly a little quartz. The outer sodic rim of the plagioclase is present only where the crystals are in contact with the matrix.

The matrix contains augite, again highly chloritised, and partly altered to a pale green hornblende, turbid plagioclase, quartz grains, turbid orthoclase, and magnetite. The plagioclase crystals, which most commonly have a core composition of An_{50}, are occasionally broken and have a compact, regularly twinned core almost free from inclusions and having a composition of An_{30}. The cores of the plagioclase are traversed by veinlets of fused material; these veinlets do not cut the sodic rims and are identical with those found in the acid rocks.

c. Basic Rocks

The basic rocks of the vent are gabbroic in appearance and are the coarsest rocks found in the vent. They contain a very small proportion of acidic material; individual basic fragments cannot be distinguished. In composition, but not in texture, the rocks are quartz-gabbros.

The rocks consist mainly of plagioclase and augite. Where the plagioclase is in contact with the matrix it has an outer shell of An_{30} surrounding a core of composition An_{50}; where /

where it is not in contact with the matrix the outer sodic shell is not present. The cores of the crystals, but not the sodic margins, are cut by veinlets of fused plagioclase exactly similar to those of the acid and intermediate vent rocks. In the basic rocks these veinlets are particularly well developed. The augite is pale in colour and much altered to chlorite. Occasionally pale green hornblende has been developed at the expense of the augite.

Fragments of the quartzo-feldspathic rocks are few in number and small in size. They consist of small patches of quartz. intergrown with turbid orthoclase.

Magnetite is very common throughout the rocks and forms large skeletal crystals. Apatite is a common accessory and spherulitic patches of green and brown chlorite occasionally occur.

Quartz is also present in crystals of unusually large size, the largest observed being approximately 3mm. in length. The crystals have highly indented outlines, sometimes contain fragments of highly turbid plagioclase, and occur as the main constituent of irregular and interrupted stringers around the basic fragments. Some orthoclase is associated with the quartz and very crude intergrowths are occasionally present. Normally both the quartz and orthoclase are granular and are thereby distinguishable from the occurrences of these minerals in /

in the acidic rocks. It is very improbable that quartz crystals of this size and form could have been derived from the metasomatised Torridonian. Their occurrence as stringers suggests that they form a scanty matrix in which the fragments lie. The most probable origin for these quartz crystals and their associated orthoclase is that they were introduced into the basic rocks, by the gases concerned in the formation and development of the vent.

3. CONCLUSIONS

The vent is occupied by an assemblage of pyroclastic acidic and basic fragments lying in a finer matrix. The rocks contain broken plagioclase crystals and their composition varies from acidic in the neighbourhood of the metasommatised Torridonian in the south-east to basic near the gabbro in the north-west.

The vent rocks contain two distinct types of plagioclase crystals, one type having a core of composition An_{35} and the other of An_{50}. Where plagioclase crystals of either type are in contact with the matrix of the rock a rim of plagioclase of composition An_{30} surrounds the cores. The cores of the more sodic plagioclase are identical with the plagioclase found in the metasomatised Torridonian; the more calcic increase steadily in abundance to the north-west and have presumably

presumably been derived from the gabbro. The cores of both types of plagioclase appear to have been fused along cracks to form veinlets. At atmospheric pressure a dry melt of plagioclase of composition An_{35} should fuse at 1,210°C and one of composition An_{50} at 1,270°C. (Bowen, 1913). In the presence of water vapour, however, the melting point of albite is lowered with increase of vapour pressure (Goranson, 1938) and it is reasonable to expect that the melting points of the other plagioclases would also be lowered. If the vent were filled with a mixture of rock fragments and gas with an average specific gravity of 2 the pressure due to load at a depth of 5km. (a reasonable estimate of the original depth of the part of the vent now exposed at the surface) would be of the order of 1,000 bars (metric atmospheres). Under such conditions the approximate fusion point of An_{35} would be 980°C and of An_{50} 1,040°C. The temperature of the gases responsible for the partial fusion of the plagioclase was therefore probably greater than 1,000°C.

The sodic rims of the plagioclase are not cut by the fused veinlets and are clearly of later date. Their composition (An_{30}) and development do not depend on the composition of the core or on the position of the crystal in the vent, and they are therefore not due directly to fusion. They cannot /

cannot be due to replacement because (a) they are developed only where the plagioclase is in contact with the matrix and (b) they have a sharp or fairly sharp boundary with the core. They can have been formed only from material which percolated through the interstices between the fragments and was of homogeneous composition throughout the vent. This leads to the conclusion that the sodic rims of the plagioclase were deposited from the gases passing up the vent.

The occurrence in the basic rocks of the vent of large irregular quartz crystals and of granules of orthoclase, neither of which can have been mechanically derived, indicates that these minerals were also crystallised from material transported by the vent gases. Such crystals are not found in the acid and intermediate rocks of the vent where, however, the presence of considerable quantities of mechanically derived quartz and orthoclase would provide numerous nuclei for the deposition of these minerals from the gases. Only in the basic rocks, where suitable nuclei were scarce, were the large crystals formed.

The high degree of chloritisation of the augite in the vent rocks shows that the vent gases introduced water, and the presence of abnormally great quantities of apatite throughout the vent indicates that phosphorus or its compounds were similarly introduced.

The /

The rocks of the vent show that, during and after the last period of activity, the gases passing up the vent attained for some period at least a temperature greater than 1,040°C. These gases were charged with significant quantities of K, Na, Ca, Al, Si, P, and H_2O.

The rocks of the aureole also provide evidence relating to the conditions prevailing in the vent.

The recrystallised sediments have suffered no large-scale introduction of material, but have been exposed to high temperatures. Goranson (1932) showed that under a pressure of 980 bars and with 7% of water present recrystallisation took place in silica-bearing rocks at a temperature of 600°C. It is probable that the recrystallisation of the Torridonian rocks took place under similar conditions of pressure, temperature, and the presence of water vapour in the outer part of the recrystallised zone.

In the north-west of the zone pseudomorphs of quartz after tridymite are present indicating that the temperature exceeded 870°C during the metamorphism.

Adjacent to the veinlets of quartz, chlorite, and apatite, which traverse the recrystallised rocks, the orthoclase is kaolinised and the ferro-magnesian minerals are converted to chlorite. The veins have probably originated from silica mobilised /

mobilised and transported by water vapour at a high temperature; the source of the silica possibly lay to the north-west within the zone of metasomatised sediments.

The rocks of the recrystallised zone have been formed at temperatures ranging from 600°C to over 870°C. They have been invaded by veinlets of mobilised quartz accompanied by chlorite and apatite and superheated steam. It is interesting to note that biotite of metamorphic origin occurs in the aureole of the gabbro beyond the outer limit of the recrystallised sediments of the vent aureole. This biotite appears to have been formed at temperatures lower than 600°C.

The metasomatised sediments have been enriched in K, Na, Ca, Al, Fe, Mg, and P and have lost a corresponding amount of Si which has possibly supplied the veinlets found in the recrystallised rocks. The gases of the vent have been shown to have contained H_2O and compounds of K, Na, Ca, Al and P, and represent an obvious immediate source for these elements. The source of the Fe and Mg is less obvious. Possibly they were also supplied from the vent gases, which could have either brought them up from below or derived them from the basic fragments in the vent. Since no other source appears to be available these two elements are presumed to have been supplied by the vent gases.

The metasomatised rocks lie between the vent rocks, which attained /

attained a temperature of over 1,040°C, and the recrystallised rocks which, on their north-western margin, were heated to over 870°C. The metasomatised rocks must therefore have been formed at temperatures between these two extremes.

It is concluded (a) that the metasomatised rocks were formed by the introduction of K, Na, Ca, Al, Fe, Mg, and P into Torridonian sediments; (b) that the gases passing up the vent supplied the introduced material; and (c) that the metasomatism took place at temperatures ranging from 870°C to over 1,000°C.

The most highly metasomatised rocks of the vent aureole and the most acid rocks of the vent both resemble the micro-granite of the west of the Isle of Rhum. All these rocks have been formed essentially by the extensive metamorphism of the Torridonian Sandstone; in the west of the island the cause of the alteration is unknown, in the east the evidence indicates that the alteration was caused by hot gases containing considerable quantities of various elements in a reactive state. The similarities in the rocks from the eastern and western occurrences suggest that they have had a similar origin; the difference in scale between the two occurrences - the western microgranite being many hundreds of times larger than the eastern occurrence - suggests that the modes /

modes of origin, though having much in common, may not have been identical. Furthermore the western microgranite does not contain broken plagioclase crystals nor recognisable fragments of basic rocks. At the present stage in the investigation into the origin or origins of the acid rocks of Rhum it is only possible to say that the two occurrences of microgranitic rocks show a distinct resemblance to each other and that they were both formed by the metasomatic metamorphism of Torridonian Sandstone.

Dr. Reynolds (1951) has described from Slieve Gullion acidic rocks which have a similar mode of occurrence to the vent rocks of the east of the Isle of Rhum. These rocks transgress the layered series of Slieve Gullion, which, where they adjoin the transgressive masses, have been locally fused. The transgressive rocks consist of mechanically derived fragments of Newry granodiorite which have been converted to granophyre and they also contain an admixture of fragments derived from the layered series. This mixture of rock fragments has been metamorphosed by hot ascending gases and converted into a rock identical with the marscoite of Skye, (Harker, 1904) and very similar to the rocks of the vent on Rhum. The latter resemblance is especially marked in the case of the plagioclase. The cores of the crystals in both the Slieve Gullion and Rhum occurrences contain veinlets of fused material which end abruptly against the sodic outer parts /

parts of the crystals. At Slieve Gullion metasomatism has taken place and the fragments have been enriched in Si and K and impoverished in Na, Al, Fe, Ca, Mg, Ti, P, and Mn. In a later paper (1952) Dr. Reynolds showed that the temperature of the ascending gases which partially fused the plagioclase was "near but not likely to be lower than 1,355°C."

Both in origin and their nature the transgressive rocks of Slieve Gullion and the rocks of the vent in the east of Rhum show the closest similarities. They differ in composition, however, since the Slieve Gullion rocks (granophyres) were mainly derived from Caledonian granodiorite whereas those of the Rhum vent were derived from Torridonian Sandstone (microgranite) and Tertiary basic rocks (quartz-gabbro) or from mixtures of these two parental materials (marscoites).

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V. The Age Relationship of the Granophyre and Basalt of Orval, Isle of Rhum

BY
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The Age Relationship of the Granophyre and Basalt of Orval, Isle of Rhum

By GEORGE P. BLACK

ABSTRACT

On Orval, in the Isle of Rhum, Tertiary plateau lavas directly overlie the granophyre of the ring-complex. Judd considered that the Orval basalts rest unconformably upon an old land surface cut in the granophyre ; but on the supposed existence of veining and metamorphism later workers, in particular Geikie and Harker, concluded that the granophyre had intruded the volcanic pile. The author's re-examination of the Orval rocks supports Judd's early interpretation.

INTRODUCTION

ORVAL is a peak in the west of Rhum. Near the summit an outlier of Tertiary olivine-basalt lavas rests on the granophyre which forms the underlying and major part of the hill. The lavas cover a quadrilateral area of approximately one-sixth of a square mile. The present upper surface is roughly horizontal, but the lower surface dips in a direction east of north. As a result the lavas vary in thickness from 500 feet on the north and east sides of the quadrilateral to zero on the south and west sides. The northern and eastern boundaries are marked by cliffs some 200 feet high, which reproduce in miniature the scenic features of the well-known Storr ridge in north-east Skye.

Neighbouring hills, to which reference will be made later, include Fionn-Chra, with Tertiary basalt lavas resting on Torridonian Sandstone, the basalts themselves being covered by flows of mugearite ; and Bloodstone Hill, where mugearites directly overlie the Torridonian Sandstone with no intervening basalts (Text-fig. 1).

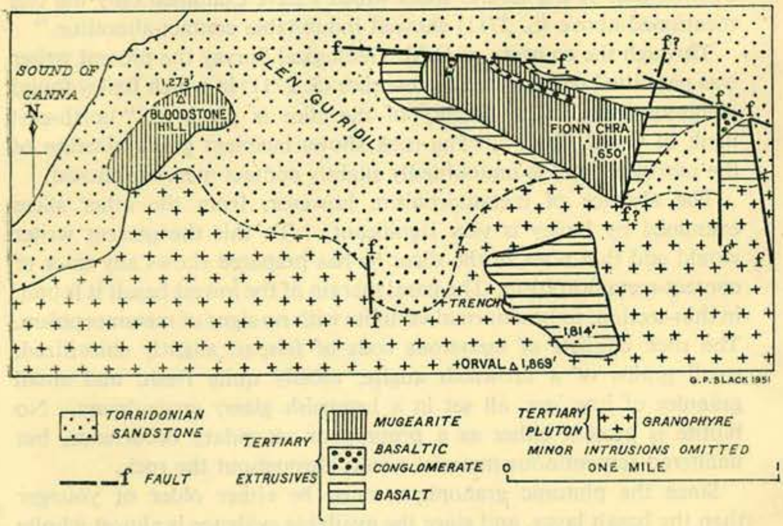
The granophyre of Orval is an integral part of the Tertiary plutonic complex of Rhum, while the basalts are part of the Tertiary lava plateau of the same island. A study of the relations of the basalts and granophyre of Orval may therefore help to establish the time-sequence of igneous activity in Rhum.

PREVIOUS WORK ON THE ORVAL AREA

Judd (1874, p. 254) expressed the view that the basalt lavas rest unconformably on the granophyre. He adduced no supporting evidence, possibly because he believed his view to be self-evident.

On the other hand, Geikie (1897, vol. ii, p. 404) stated that an outlier of lavas " lies upon the porphyry (i.e. granophyre) of Orval as a cake that dips gently northward. . . . It has undergone contact-metamorphism and tongues from the underlying rock project up into it ". From this it is clear that he believed the granophyre to be younger than the overlying lavas.

Harker (1908, p. 60) supported Geikie's view. " In two localities the basaltic lavas assume a somewhat different aspect in the field, being metamorphosed in proximity to plutonic intrusions . . . One of the localities alluded to is the north-eastern shoulder of Orval, in Rhum, where a patch of basalt half a mile long rests on, and is surrounded by, granite which has produced in it a noteworthy degree of metamorphism."



TEXT-FIG. 1.—Map of the geology of the neighbourhood of Orval.

More recently Bailey (1944, p. 184) holds the view that the metamorphism is only slight, while Tomkeieff (1942, p. 3) states that " The lavas near the granophyre are altered and the granophyre, in its turn, assumes a fine-grained texture near the contact with the lavas ".

On the whole, therefore, Geikie's view is at present generally accepted.

RE-EXAMINATION OF PREVIOUS EVIDENCE

Since 1949 the present writer has been engaged in investigating the southern and western areas of the Isle of Rhum. A thorough examination of the exposures around Orval has been included in this research.

(*a*) *Geikie's " Tongue of Granophyre "*

At the base of the lava cliffs blocks were found consisting of melanocratic rock traversed by a network of leucocratic veins. It is possible that Geikie assumed that these had fallen from the lava cliffs above.

In fact, detailed examination has shown that these blocks are glacial erratics of peridotite. The veins are the felspathic veins characteristic of much of that rock in Rhum. The basal lava even though coarsely jointed, shows no signs of " tongues from the underlying granophyre ".

(*b*) *Metamorphism of the Basalts*

Bailey (1944, p. 184) states : " The granophyre has altered the lavas so little that of the several slices which I have examined only the one mentioned above (S. 2711) showed indubitable contact-alteration."

Through the courtesy of H.M. Geological Survey the present writer was permitted to examine this one slice (S. 2711) in which Bailey found metamorphism. The locality of the slice is given as " north-east flank of Orval, Rum ". The rock shows incipient granulitization of the pyroxene, and is undoubtedly slightly contact-metamorphosed.

The absence of metamorphism, however, from the other slices examined by Bailey is very significant. To this the present writer would add that none of the slices he has prepared shows any trace of contact-metamorphism. The basal margin of the lowest basalt is found in thin-section, to be a normal variolite with no signs of metamorphism. The rock consists of numerous rods of felspar, slightly chloritized, small grains of a brownish augite, mostly quite fresh, and small granules of iron ore, all set in a brownish glassy groundmass. No biotite is present either as a primary or secondary occurrence, but unaltered serpentinous material occurs throughout the rock.

Since the plutonic granophyre must be either older or younger than the basalt lavas, and since the available evidence is almost wholly in favour of the former alternative, the exceptional occurrence of slight metamorphism in the lavas, as found in S. 2711, would appear to be purely local and due to some agency other than the granophyre. It may have been caused by some minor igneous body such as a dyke. Unfortunately the locality of the slice was not sufficiently clearly defined to make further investigation possible.

Further Evidence

In the course of the present investigation much new evidence bearing on the problem under discussion has been obtained.

(*a*) The thickness of the basalt pile throughout the region was investigated. On Orval the basalts show a maximum residual thickness of 500 feet, despite an upper surface determined by erosion. On Fionn-Chra the basalts, resting on Torridonian Sandstone and covered by mugearite, are 150 feet thick. At Bloodstone Hill, where mugearites lie directly on Torridonian Sandstone, basalt is lacking. Explanation of this rapid variation of thickness would not be rendered easier by accepting Geikie's view that the lava pile on Orval has been invaded and presumably partially destroyed by the underlying granophyre.

(*b*) The variety of rocks with which the granophyre is in contact suggested an inquiry into the occurrence of xenoliths. Wherever the granophyre is in contact with a basic rock of undoubted greater age, it has been found to be crowded with basic fragments of all sizes for many feet from the contact. Examples of this occur where the granophyre is in contact with gabbro (Harker, 1908, p. 105), and with the peridotite (ibid., p. 105). Along the contact of the basalts and granophyre on Orval, however, the present writer found the granophyre to be free from xenoliths. Moreover, it has a content of ferromagnesian material no greater than that normally found in parts of the mass furthest removed from all contacts. This absence of xenoliths and of reaction products is inconsistent with Geikie's hypothesis.

(*c*) Specimens, equally exposed to present-day weathering were taken from the granophyre in proximity to its contact with the basalt ; and these were examined microscopically with a view to determining the presence or absence of a fine-grained chilled margin. The granophyre 5 feet below the lavas is of a normal coarse type with a grain-size of approximately 1·5 mm. The orthoclase of the rock is extensively clouded, generally brownish, and in parts almost opaque. The soda-plagioclase, however, is much less decomposed. The whole rock is stained in places with limonitic material. Specimens taken from nearer the margin have the same grain-size of about 1·5 mm. The orthoclase, however, is more turbid, the turbidity is seen to be affecting the plagioclase, and the limonitic staining is more pronounced. There is therefore no sign of a fine-grained margin such as would be expected in an igneous contact. The upward increase of the turbidity in the felspar and of the limonitic staining suggests that part of this decomposition had been achieved in pre-basaltic times. The evidence is again consistent with the view that the contact plane is an erosion surface.

(*d*) A microscopic examination was also made of specimens collected from the lower margin of the lava flow in contact with the granophyre. These specimens contain small crystals of quartz and the question at once arises whether they are xenocrysts or not. If this quartz had crystallized from the basalt it should be interstitial. The quartz crystals which actually occur, however, are rounded in shape ; they often have a strained extinction ; and the basalt does not appear to have reacted with them to any appreciable extent. Moreover, similar quartz crystals, again with a strained extinction, occur in the near-by granophyre and Torridonian Sandstone. The quartz crystals in the basalt, therefore, must be considered as xenocrysts. The presence of this xenocrystal quartz in the basal basalt indicates that this flow may have traversed an arenaceous or granite surface. If this be so, the present basal flow must be part at least of the original basal flow. Furthermore, the present base of the basalt shows all the characteristics of the fine-grained chilled margin of the flow.

(*e*) Finally, with a view to obtaining the best positive evidence, a trench was dug at the western extremity of the Orval lavas to expose the granophyre-basalt contact. The actual contact was found under two feet of drift some thirty feet below the lowest near-by natural exposure of basalt. Specimens were collected from this trench and were examined microscopically.

The crystallinity of the granophyre half an inch below the contact plane is the same as elsewhere, the grain-size being approximately 1·5 mm. The orthoclase is turbid, occasionally to the extent of becoming opaque. The soda-plagioclase is also turbid and decomposed. The hornblende is almost totally decomposed and replaced by an aggregate of limonitic material. No fragments of basic material are found, and no chilled-edge is present.

The basalt two inches above the granophyre is a fine-grained amygdaloidal rock with plagioclase phenocrysts set in a brown glassy groundmass. The amygdules consist of calcite, zeolites, chlorophaeite, and a greenish-brown serpentine. No signs of crystallization of the chlorophaeite or of alteration of the zeolites and serpentine are discernible. The entire rock has obviously suffered no metamorphism.

Between the granophyre and the basalt there is found approximately one inch of a highly decomposed rock. Such specimens as could be sectioned show the rock to be of basaltic composition but to vary widely in grain-size. The amygdule infillings of chlorophaeite and serpentine are all unaltered. This rock has clearly suffered no metamorphism. It is a fragmental deposit derived from basalt but owing to its highly decomposed state a more precise determination of its nature is impossible.

The evidence from the specimens collected from the trench disproves the supposed metamorphism of the basalts by the granophyre. On the other hand, it gives strong support to Judd's hypothesis that the basalts rest unconformably upon an erosion surface cut in the granophyre.

Conclusion

In the foregoing sections considerable evidence has been put forward against the current interpretation that the basalts of Orval were intruded and metamorphosed by the underlying granophyre. The presence of acidic veins and widespread metamorphism, claimed by Geikie, has not been substantiated. Further counter-evidence is found in the absence of xenoliths, the constant ferromagnesian content of the granophyre at all distances from the contact and the absence of a fine-grained margin in the granophyre.

Two further items of evidence are given which seem to call for a return to Judd's interpretation—the occurrence of an unmetamorphosed fragmental deposit consisting mainly of basalt at the base of the Orval lavas, and the existence of a chilled margin at the base of the lowest basalt on Orval. Furthermore, the rapid variation of the thickness of the basalt lavas of the region calls for an explanation.

The following time-sequence is in accord with all the evidence now available :—

(*a*) The granophyre was emplaced as part of the Tertiary plutonic complex of Rhum.

(*b*) Erosion exposed the granophyre, and an east-to-west river valley was cut in the rock. This river valley was slightly to the north of Orval, thus accounting for the northerly slope of the granophyre surface.

(*c*) Several basalt lavas flowed into this valley. In the earlier stages of this vulcanicity the lower part of the valley was filled by basalt, leaving the higher slopes of granophyre still exposed. The detritus subsequently supplied to the river would then naturally consist of commingled basaltic and granophyric material. Relics of this are now found as the " basaltic conglomerates " of Rhum and Canna (Harker, 1908, pp. 39–52).

(*d*) Further eruption of basalts continued until the valley was completely filled with lava, and the river was forced to cut a new channel through the lava plateau. The location of this new channel in the western part of the Isle of Rhum was some little distance to the north of the original river valley. As a result of the formation of the new river course, the basalt lavas were removed from the central and northern parts of the old river valley but remained on the southern slopes, although much diminished in thickness in places. The erosion of this new river valley is thus the cause of the variation in thickness of the basaltic lavas now seen on Orval and Fionn-Chra, and of the absence of basalt from Bloodstone Hill. Orval was definitely on the south bank, Bloodstone Hill was in the middle of the valley, and Fionn-Chra occupied a level intermediate between the two.

(*e*) Into the later valley was erupted a sufficient thickness of mugearite to cover at least part of the remaining basalt. The remnants of these flows are now seen on Fionn-Chra and Bloodstone Hill.

(*f*) Further erosion during the Tertiary and Quaternary periods eventually produced the topography of the area as seen to-day.

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106.

VI. The Tertiary Volcanic Succession of the Isle of Rhum, Inverness-shire

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107.

The Tertiary Volcanic Succession of the Isle of Rhum, Inverness-shire

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ABSTRACT

Four outliers of volcanic rocks cover an area of approximately three-quarters of a square mile in the western part of the Isle of Rhum. Although these outliers are only small remnants of the original Tertiary volcanic pile of the island, the observed sequences, combined with the recognition of six distinctive petrographic groups, make it possible to establish the following upward succession from the Torridonian Sandstone and Tertiary granophyre on which the volcanic rocks lie: (1) lower volcanic conglomerate and tuff; (2) lower basalt lavas; (3) lower mugearite lava; (4) upper basalt lavas, with unconformity above; (5) first of the upper mugearite lavas, with slight unconformity above: (6) upper volcanic conglomerate; (7) upper mugearite lavas. The total maximum thickness amounts to nearly 1,700 feet.

CONTENTS

I. Introduction

In the western part of the Isle of Rhum, four small outliers of volcanic rocks cover a total area of approximately three-quarters of a square mile. They rest unconformably on Torridonian Sandstone or Tertiary granophyre and cap the hills of West Minishal, Fionchra, Orval, and Bloodstone Hill (Fig. 1). Since the volcanic rocks—basalt, mugearite, and volcanic conglomerate—are nowhere conformably covered, their original thickness cannot be determined, but on Fionchra 1,050 feet have been preserved. The total thickness of the original lava plateau cannot have been less than this figure, and, as will be shown, there are reasons for believing that it must have been considerably greater.

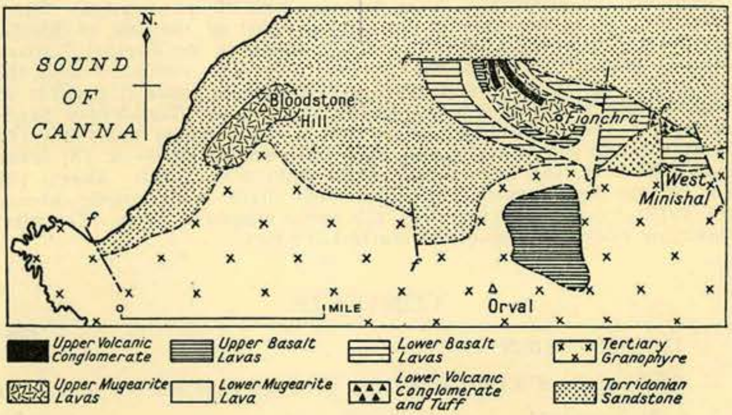

Fig. 1. Geological Map showing four Tertiary volcanic outliers in the western part of the Island of Rhum.

The volcanic rocks outcrop in a region of high relief, the lavas occurring between the 600-foot and 1,800-foot contours. Trap-featuring is pronounced and the lower hill-slopes are diversified by lava boulders, often of great size, which have fallen from the scarps above. Abundant screes frequently obscure the sub-volcanic unconformity and the lower flows.

The lavas and their associated volcanic conglomerates were first described by Macculloch in 1819. He identified them as "stratified traps" and as "basalt and amygdaloid" and noted the occurrence of chlorophaeite and heliotrope in the amygdales of the lavas of Bloodstone Hill.

Judd (1874) mentioned the existence of several outliers of lava in the west of Rhum and surmised that they rested unconformably on both Torridonian Sandstone and granophyre. The same author later published a map (1878) on which he showed the

109.

four outliers as occurrences of Tertiary basalt. Geikie (1897) added little to the earlier descriptions of the lavas but advanced the hypothesis that the granophyre had intruded the volcanic pile.

Harker (1908) mapped and described the volcanic rocks in greater detail, dividing them into a series of basalts, a series of mugearites, and two horizons of fluviatile conglomerates. He followed Geikie in believing that the granophyre had intruded the lavas and he mistakenly regarded the mugearites and some of the basalts as sills. Harker's petrographic descriptions of the lavas have recently been amplified by Tomkeieff (1942), who concluded that the mugearites and all the basalts were effusive rocks. In 1944 Bailey described the supposed contact metamorphism of the lavas by the granophyre as only slight.

Since 1949 the present author has systematically re-examined the volcanic rocks in the course of a field and petrological investigation of the rocks of Rhum. Evidence has been found (Black, 1952) which strongly supports Judd's postulated relationship of the lavas and the granophyre; in addition, probable correlations of the various volcanic rocks of the different outliers have been made possible by the recognition of their distinctive petrographic characters. As a result an integrated volcanic succession for the west of Rhum can now be established with reasonable certainty.

II. Volcanic Successions of the Outliers

The largest number of volcanic divisions in any one outlier is to be found on the hill of Fionchra, where six occur. Of the other outliers West Minishal shows two, whereas Orval and Bloodstone Hill consist entirely of one type of rock. From petrological evidence, detailed in section III, it has been found possible to correlate these incomplete occurrences with their counterparts in the more fully preserved succession of Fionchra.

(*a*) Fionchra

This outlier of volcanic rocks rests unconformably on Torridonian Sandstone except in its southernmost part, where the lavas rest on granophyre. The lavas dip at low angles to the west, the height of the base of the volcanic pile varying from 1,100 feet above sea level at the northern end to 600 feet at the western. The outlier is partly bounded by faults on the north and east and its eastern extremity is downfaulted from the main portion to the west.

In the east a poorly exposed bed of tuff, at least 20 feet thick, is found at the base of the volcanic pile. Immediately above the tuff there occur 250 feet of Lower Basalt Lavas which form the lower part of the greater part of the outlier. These Lower Basalt flows, at least five in number, are irregularly jointed and give rise to a slight development of trap-featuring. The Lower Mugearite, a single flow 150 feet thick, succeeds the Lower Basalts and forms a prominent scarp. The mugearite shows well-developed columnar jointing and also a system of closely spaced minor joints, which cause the rock to break into small rhombohedral fragments. The flow consequently has a brecciated appearance —a characteristic of all the mugearite lavas of Rhum. A further series of basaltic flows, having a maximum thickness of 50 feet, lies above the mugearite. It is doubtful if these Upper Basalt Lavas are present on all the slopes of the outlier but they are exposed in the east and west. On Orval, as described later, the Upper Basalts are seen to rest uncomformably on granophyre and to have an upper surface determined by present-day erosion. Nevertheless they are 550 feet thick and comprise at least eight flows. On Fionchra, on the other hand, the Upper Basalt Lavas (two flows) rest conformably on the Lower Mugearite and are covered by other volcanic rocks. Here, however, they are only 50 feet thick and their upper surface is an unconformity which must represent a considerable amount of erosion.

Above the unconformity, on Fionchra, 560 feet of mugearite flows rest directly upon the eroded surface of the basalts. These Upper Mugearite Lavas, which show prominent trap-featuring and columnar jointing, form the upper part of Fionchra and are the youngest volcanic rocks preserved in Rhum. Some 50 feet above their base, there occurs a local development of volcanic conglomerate which has a maximum thickness of 20 feet and represents a minor unconformity within the Upper Mugearite Series.

(*b*) West Minishal

The low hill of West Minishal is capped by a down-faulted outlier of volcanic rocks more than 300 feet thick. A fluviatile volcanic conglomerate, the base of which is nowhere exposed, forms the lower part of the visible volcanic succession in the north but thins away towards the south where it is missing. Four flows of basalt, with a total thickness of 150 feet, lie almost horizontally on this conglomerate and on Tertiary granophyre. The basalts, which are irregularly jointed and give rise to some trap-featuring, are the highest volcanic horizon preserved on the hill.

(*c*) Orval

To the north-east of the summit of Orval, a patch of almost flat-lying basaltic lavas, 550 feet thick and consisting of at least eight flows, rests unconformably on granophyre; the surface of the junction rises from 1,250 feet above sea-level in the north to 1,800 feet in the south. Scarps and steep slopes mark the margins of the outlier but the lavas themselves form a gently sloping trap-featured tract of country. The columnar jointing of the lavas is well seen on the edges of the scarps.

(*d*) Bloodstone Hill

Four hundred and fifty feet of mugearite lavas cap the summit of Bloodstone Hill and form a series of bold scarps and steep grassy slopes. The lowest lava rests on an uneven surface, partly of granophyre and partly of Torridonian Sandstone, the base of the volcanic pile varying in height from 800 feet in the north-west to 1,000 feet in the south-east. Four or five flows are present and dip southwards at a very low angle. Columnar jointing and trap-featuring are well developed.

III. Petrology of the Volcanic Rocks

(*a*) Lower Volcanic Conglomerate and Tuff

The basal tuff on Fionchra, brownish-green in colour, weathers to a sandy material and contains no large fragments. It consists of angular quartz and plagioclase grains, broken crystals of pyroxene, calcite pseudomorphs after olivine, and grains of serpentine, all set in a matrix of calcite and serpentine.

Where the volcanic conglomerate at the base of the outlier of West Minishal is exposed, it consists of unaltered rounded fragments, up to a foot in diameter, set in a fine, much decomposed, clay-like matrix probably derived from highly weathered lavas. Most of the fragments are basalt, probably of local derivation, but gneisses of Lewisian type, arkoses resembling those of the Torridonian, and Tertiary igneous rocks (other than basalt) also occur. Among the last-mentioned group, there have been recognised granophyre and associated hybrid rocks identical with those of nearby exposures, eucrites probably from the east of Rhum, and quartz-felsites like those described by Harker (1908, pp. 139, 140) from the east and south. The preponderance of basalt and the assemblage of water-worn fragments suggest that the volcanic conglomerate was deposited by a river flowing from the east and carrying a load derived from pre-existing agglomerates and other materials. The site of the present outlier of West Minishal occupied a position on the southern bank of this Tertiary river.

Judging from the close association of tuffs and volcanic conglomerates that is known to occur on the neighbouring island of Canna (Harker, 1908, pp. 40-49), it seems probable that the basal tuff of Fionchra may correspond in age to part of the volcanic conglomerate of West Minishal. Unfortunately the paucity of exposures of these rocks makes an exact correlation impossible.

(*b*) Lower Basalt Lavas

The Lower Basalt Lavas of Fionchra are dark green or black rocks which are sparsely amygdaloidal. They contain phenocrysts of plagioclase and olivine set in a groundmass of plagioclase and augite, with accessory amounts of magnetite. The plagioclase phenocrysts (Table I) show repeated complex twinning, and are slightly zoned. The olivine phenocrysts, which are less abundant, are normally subhedral and show incipient serpentinisation along numerous curving cracks; they frequently form glomero-porphyritic aggregates with plagioclase.

The plagioclase of the groundmass (Table I) is simply twinned, slightly zoned, and occurs as tabular crystals. The crystals appear in thin section as laths which are frequently aligned by flow. The alignment swings round the phenocrysts but is often continued by laths totally enclosed within ophitic augites (see Clark, 1952, this volume, p. 69). The augite of the groundmass, purple or purplish-brown in colour, occurs in two common habits—granules and ophitic plates—both of which may be found in the same thin section. Magnetite, in accessory amounts, occurs as small grains. Near amygdales, however, it may occur as long slender rods. A pale green chlorite has locally replaced augite and plagioclase, and the rare amygdales consist of chlorite, serpentine, calcite or zeolites in varied associations.

The basalts of West Minishal resemble the Lower Basalt Lavas of Fionchra so closely that there can be no doubt that they are a detached part of the same group of flows. In all their main petrological characters these two occurrences of basalts differ from the Upper Basalt Lavas but are themselves identical.

(*c*) Lower Mugearite Lava

The Lower Mugearite of Fionchra is a dark grey vitreous-looking rock which, in its upper part, contains small chlorite-filled amygdales. It consists of numerous small phenocrysts and microlites of plagioclase, rare serpentine pseudomorphs after relatively large olivine crystals, small phenocrysts and grains of augite, and chloritic material set in a dark brown glassy matrix which is dusted with opaque specks, probably of iron-ore. Skeletal growths of magnetite are also present. The plagioclase phenocrysts (Table I) are normally almost euhedral and slightly zoned and often include small patches of the glassy matrix. The groundmass plagioclase is oligoclase and occurs as slender irregularly zoned laths which are either simply twinned or untwinned. A flow alignment is seen here and there. Small granules of a brownish augite, partly altered to a pale green chlorite, are sparsely present in the groundmass.

(*d*) Upper Basalt Lavas

On Fionchra the rocks of this division are dark green and holocrystalline and comprise two flows: the lower containing abundant plagioclase phenocrysts and the upper being almost non-porphyritic. The groundmass of both flows consists of plagioclase, augite, and olivine with accessory amounts of magnetite. The plagioclase phenocrysts (Table I) are multiply-twinned and many of the sections show concentric zoning from a more calcic core to a more sodic margin. The groundmass plagioclase is seen in thin section as simply twinned, often zoned, and almost unaltered laths. The augite—a brown or brownish-purple variety, altered here and there to a greenish chlorite—occurs as large ophitic plates, or as small granules. Olivine occurs as subhedral crystals averaging 0·5 by 0·2 mm, with occasional much larger crystals up to 1·5 mm long. It is colourless and always partly altered to a green serpentine along a network of curving cracks. Small grains of magnetite occur throughout the rocks, and amygdales containing serpentine or chlorite, and rarely opal, are occasionally present.

The basalts of the Orval outlier closely resemble the upper flow of the Upper Basalts of Fionchra. In hand specimen the two rocks are indistinguishable and in thin section they are seen to have very similar petrographic characters. All the Orval lavas contain sporadic phenocrysts which are almost invariably of plagioclase. The groundmass of the Orval basalts is very similar to that of the Upper Basalts on Fionchra but the granularity is somewhat greater (Table I). Very rare needles of apatite are found in the Orval basalts.

The Upper Basalts of Fionchra, along the strike from Orval, rest conformably on the Lower Mugearite at a height of 1,150 feet, whereas on Orval the basalts rest unconformably on the granophyre at heights varying from 1,250 to 1,800 feet. The similarities in mineral composition and texture between the two occurrences indicate that they belong to the same volcanic division, but their variations in level suggest that the two flows on Fionchra belong to a lower part of the Upper Basalt Lavas than is represented on Orval.

(*e*) Upper Mugearite Lavas

The Upper Mugearite Lavas of Fionchra are vitreous-looking rocks which are dark grey when fresh and light grey when weathered. They consist of small phenocrysts of plagioclase, augite and completely serpentinised olivine, in a groundmass of minute plagioclase laths, augite, chlorophaeite and skeletal magnetite, set in a dark brown isotropic glass. Amygdales, commonly occupied by zeolites or by opal and chlorophaeite, are of frequent occurrence.

114.

The plagioclase phenocrysts (Table I) are fresh and often euhedral. The augite phenocrysts ($0{\cdot}25 \times 0{\cdot}15$ mm) are small brown subhedral crystals, and tend to occur in groups. No unaltered olivine phenocrysts remain but occasional serpentine pseudomorphs occur; these are normally small and rounded but some are euhedral (after olivine) and up to 1·5 mm in length.

The plagioclase of the groundmass (Table I) occurs as small, fresh rarely twinned laths and microlites which are strongly zoned. The augite is a pale brown variety which occurs as rounded grains.

The mugearite lavas of Bloodstone Hill are very similar to the rocks just described. They differ, however, in containing magnetite phenocrysts up to $0{\cdot}5 \times 0{\cdot}4$ mm; small octahedra of magnetite in a dark brown almost opaque glassy matrix; and celadonite and bowlingite among the amygdale minerals. It is noticeable that the glassy matrix becomes more crystalline and lighter in colour in the neighbourhood of the amygdales.

The mugearites of Bloodstone Hill show greater resemblance to the Upper Mugearite Lavas of Fionchra than they do to the Lower Mugearite. The base of the volcanic pile on Bloodstone Hill is some 800 to 1,000 feet above sea-level and the heights of the lower limits of the Upper and Lower Mugearite Lavas on the westernmost part of Fionchra are 1,000 and 850 feet respectively. The slope of the base of the lavas on Fionchra is 300 feet per mile in a westerly direction. Since Bloodstone Hill lies two-thirds of a mile to the west of the nearest point of the Fionchra outlier and all the known faults between the two downthrow towards the west, the maximum heights of the bases of the Upper and Lower Mugearite Lavas to be expected on Bloodstone Hill would consequently be 800 and 650 feet respectively. The mugearites of Bloodstone Hill therefore occur in a position where Upper Mugearite Lavas are to be expected. This coincidence of position and petrological resemblance suggests that the Bloodstone Hill mugearites are part of the Upper Mugearite Lavas.

(*f*) Upper Volcanic Conglomerate

This horizon occurs only on Fionchra some 50 feet above the base of the Upper Mugearite Lavas, and consists of sparse boulders up to six inches in diameter in a clay-like matrix. Most of the boulders are of Tertiary volcanic rocks but gneisses of Lewisian type, together with quartz-felsite, probably derived from the south or east of Rhum, also occur. The rounded and water-worn boulders point to the existence of a westward-flowing river after the eruption of the first of the Upper Mugearite Lavas.

TABLE I

LAVAS		PLAGIOCLASE*		AUGITE (Groundmass)		OLIVINE
		Phenocrysts	Groundmass	Ophitic	Granular	
Upper Mugearite Lavas		An_{60} 0·4 × 0·15 mm	An_{30} 0·08 × 0·02 mm	—	0·04 mm across	Up to 1·5 mm in length
Upper Basalt Lavas	Orval	An_{70} 2·5 × 1·5 mm	An_{65} 0·4 × 0·15 mm	2·5 × 1·5 mm	0·25 mm across	0·2 mm across to 0·5 mm across
	Fionchra	An_{70} 1·2 × 0·4 mm	An_{65} 0·35 × 0·08 mm	1·2 × 0·8 mm	0·07 mm across	0·2 × 0·15 mm
Lower Mugearite Lavas		An_{45} 0·8 × 0·25 mm	An_{25} 0·15 × 0·02 mm	—	0·04 mm across	0·25 × 0·15 mm
Lower Basalt Lavas		An_{60} 0·8 × 0·35 mm	An_{55} 0·15 × 0·15 × 0·03 mm	0·8 × 0·4 mm	0·04 mm across	0·7 × 0·25 mm

* The composition of the plagioclase was determined from the maximum symmetrical extinction angles shown by albite twins and, in the case of mugearites, from the maximum extinction angle of microlites in conjunction with the relative relief to Canada balsam.

IV. The Volcanic Succession of Rhum

With the aid of the evidence detailed above the volcanic rocks of the various outliers have been correlated. All the main divisions so far recognised are found on Fionchra but individual divisions may reach their greatest known thickness elsewhere. In the following summary (from above downwards) the incomplete successions of the four volcanic outliers are integrated:

7. Upper Mugearite Lavas (maximum thickness on Fionchra, at least 510 feet; also found on Bloodstone Hill). The groundmass consists of oligoclase, augite and magnetite, with much glass, and contains phenocrysts of labradorite, augite, and completely altered olivine. Many amygdales are present, occupied by opal, zeolites, chlorophaeite, celadonite, and bowlingite.

6. Upper Volcanic Conglomerate (maximum thickness on Fionchra, 20 feet). This horizon is water-laid and contains sparse large fragments set in a clay-like matrix. Tertiary volcanic and plutonic rocks and Lewisian (?) gneiss occur.

Unconformity

5. First of the Upper Mugearite Lavas (maximum thickness on Fionchra, 50 feet; possibly occurring on Bloodstone Hill). Identical with 7.

Unconformity

4. Upper Basalt Lavas (maximum thickness on Orval, at least 550 feet; also found on Fionchra). Medium grained and macro-porphyritic, with sparse labradorite-bytownite phenocrysts in a groundmass of labradorite, brown augite and olivine.

3. Lower Mugearite Lava (maximum thickness on Fionchra, 150 feet). Phenocrysts of labradorite are set in a groundmass of oligoclase, pale brown augite, skeletal magnetite, and brown glass. Rare pseudomorphs after olivine occur and small amygdales of chlorite are found in the upper part of the flow.

2. Lower Basalt Lavas (maximum thickness on Fionchra, 250 feet; also found on West Minishal). Fine-grained and microporphyritic, with numerous phenocrysts of labradorite and olivine in a groundmass of sodic labradorite, purplish augite, and magnetite.

1. Lower Volcanic Conglomerate and Tuff (maximum thickness on West Minishal, at least 150 feet; also found on Fionchra). In the water-laid conglomerate there occur numerous boulders of Tertiary volcanic and plutonic rocks and also of Pre-Cambrian rocks. The tuff consists of fragments of quartz, plagioclase, augite, completely altered olivine, and serpentine in a matrix of calcite and serpentine.

Unconformity

Tertiary granophyre and Torridonian Sandstone.

V. CONCLUSIONS

The maximum total thickness of this succession, in which two inter-volcanic unconformities occur, is at least 1,680 feet. As the upper part of the volcanic pile has been removed by denudation the total thickness of the volcanic rocks erupted on the Isle of Rhum after the emplacement and denudation of the granophyre, must have exceeded this figure, possibly by many hundreds of feet.

The outliers of volcanic rocks on Rhum are demonstrably remnants of a widespread lava plateau which once covered much of the island and probably extended over what are now the neighbouring islands of Eigg, Muck, Canna, and Sanday. Accordingly the volcanic successions of these islands would be expected to resemble the succession observed on Rhum. Basalt and mugearite lavas and volcanic conglomerates occur on all the above-mentioned islands and have been described by Harker (1908, pp. 39-60 and 115-134). In his account he separated from the other volcanic rocks the mugearite lavas and the central columnar portions of the basalt flows, mistakenly regarding them as sills intrusive into the volcanic pile. Consequently his descriptions cannot be used as a basis for the division of the lavas into the distinct petrographic groups necessary for the establishment of a succession. It can be said with certainty only that the volcanic rocks of Eigg, Muck, Canna, and Sanday are petrographically very similar to those of Rhum, and that agglomerates and volcanic conglomerates everywhere occur at or near the base of the volcanic pile and are closely followed by a horizon of mugearite on the islands of Eigg and Muck.

Many of the lavas of Skye, also described by Harker, are very similar petrographically to those of Rhum, but no detailed volcanic succession has yet been recorded. Agglomerates and volcanic conglomerates (Harker, 1908, pp. 15-28) again form the basal members of the volcanic pile and are followed by a great thickness of lava flows—mainly of basalt (*ibid.*, pp. 29-40) but with local developments of rhyolite, trachyte, and andesite (pp. 55-62)—parts of which Harker interpreted as being "sills" of dolerite (pp. 235-253) and mugearite (pp. 256-269). These "sills" are now considered to be lava flows; Richey (1948), for example, makes no reference to sills in the lavas. The volcanic succession of Rhum is in part comparable to the alternations of basalt and mugearite occurring in the neighbourhood of Roineval and Druim na Criche in Skye, where, however, the mugearite is generally part of a composite lava flow (Kennedy, 1931), such composite flows being found at intervals in a dominantly basaltic succession. In Rhum, on the other hand, no composite lava flows are known and a group of at least eight successive flows of mugearite forms one of the main divisions of the volcanic pile.

In the Island of Mull (Bailey and others, 1924) mugearite lavas occur at intervals in the Plateau Group of lavas. One occurrence—the Ben More mugearite—can be traced over a considerable area and appears in places to consist of more than one flow. Other less persistent mugearite occurrences are also known. In Mull as in Rhum the mugearite lavas occur as simple flows and alternate with groups of basalt lavas. Although the relative proportion of mugearite in Mull is considerably less than in Rhum, the volcanic succession of the latter island probably finds its closest analogue in the Plateau Lavas of Mull.

Mugearite lavas of Tertiary age are not known from Ardnamurchan, Arran or Antrim. The well-known tholeiitic basalts of the Giant's Causeway type in North Antrim (Tomkeieff, 1940) are very different from any found in Rhum. Elsewhere in Antrim the flows above the Interbasaltic Horizon (the upper series) are olivine-basalts like those of the lower series (Patterson, 1950). Both resemble the Lower Basalts of Rhum and the only clue towards a possible correlation is provided by the occurrence in Northern Ireland of rhyolites and associated intrusions which are generally considered to have been erupted or emplaced during Interbasaltic times. If this conjecture be correct, then there is a rough analogy between the sequence in Rhum, granophyre followed by olivine-basalt, and that of parts of Northern Ireland where it would be rhyolite followed by olivine-basalt.

The volcanic assemblage still preserved in the Isle of Rhum differs from that of other parts of the British Tertiary volcanic province in that mugearite lavas comprise approximately 40 per cent. of its total known thickness.

VI. Acknowledgements

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II. THE BASIC HYPABYSSAL ROCKS OF THE WEST OF THE ISLE OF RHUM

THE BASIC HYPABYSSAL ROCKS OF THE WEST OF THE ISLE OF RHUM

1. INTRODUCTION

Numerous small bodies of basic hypabyssal rock occur in the west of the Isle of Rhum. Within the tract of the acid rocks pre-granitic and post-granitic basic bodies can be distinguished, but elsewhere the distinction cannot normally be made.

Seven small sills and several dykes of pre-granitic age occur within the acid rocks. Another sill, intrusive into the Torridonian, is thought to be also pre-granitic for reasons outlined below. It is prpbable that pre-granitic dykes cut the Torridonian but these cannot be distinguished in the field from the very numerous post-granitic dykes.

The post-granitic, basic hypabyssal rocks form abundant dykes and sheets irregularly distributed throughout the west of Rhum. The great majority of these dykes and sheets are basaltic; several are composed of augite-andesite and a few are of mugearite-tachylyte.

2. THE PRE-GRANITIC SILLS AND DYKES

(i) SILLS

Seven /

Seven basic sills, all metamorphosed and therefore demonstrably pre-granitic, lie within the acid rocks. Another sill, which has intruded unmetamorphosed Torridonian a few yards to the north of the faulted contact of the graphophyre, is believed to be pre-granitic on account of its petrographic similarity to the seven undoubted pre-granitic sills and its contrast with the post-granitic intrusions.

The largest metamorphosed sill occurs in the Monadh Mhiltich, 600 yards south of the summit of Minishal, has a poorly exposed outcrop some 250 yards in diameter, and a thickness of some 130 feet. It lies almost horizontally on the graphophyre and its upper surface is determined by erosion; its western limit is determined by a fault. Another large mass, with an outcrop 250 yards from east to west and 50 yards from north to south, forms the summit of Gualann na Pairce half a mile north-north-east of Harris Lodge. This sill, which is well exposed, also lies almost horizontally on the graphophyre and has an upper surface determined by erosion. A third sill of comparable size outcrops on the south-western flank of Ard Nev (See Plate IX, Fig 1); it is well exposed and lenticular in cross section. Two small sills of lenticular cross section outcrop along the eastern base of Ard Nev /

Nev near Dornabac Stables; these two sills are poorly exposed. Two other small sills are known, one 1¾ miles north-north-east of Harris Lodge and the other half a mile south-west of the summit of Minishal. Both are poorly exposed; the former appears to be lenticular in cross section whereas the form of the latter is not known.

All seven metamorphosed sills were originally composed of very similar, more or less ophitic olivine-dolerites, some of which contain hypersthene. The margins were, before metamorphism, generally amygdaloidal and relatively fine in grain. In the Monadh Mhiltich sill layers of dunite now serpentinised in part are present at a height of some 100 feet above the base. This sill is the largest and thickest of the seven undoubted pre-granitic sills and the presence of dunite raises a tantalising problem in suggesting that differentiation occurred.

In each sill the metamorphism was most intense at the margins and died away inwards; it was only slight at a distance of 30 or 40 feet from the margins and was negligible at a distance of 100 feet. The sills are cut by small veins along which comminution has occurred. Veins of chlorite also cut the rocks and patches of epidote occur. The metamorphism /

morphism had very variable effects; even in a single thin-section parts of the rock are seen to be highly altered and converted to aggregates of chlorite and serpentine while other parts are almost unaffected. As a result of the metamorphism the plagioclase crystals are often bent and are sometimes partly replaced by kaolin or chlorites; locally some albitisation has occurred and in places scapolite has formed. Concentric zoning from calcic cores (approximately An_{70}) to sodic margins (as sodic as An_{35}) is very frequent; the difference between the cores and margins of the plagioclase is greatest at the margins of the sills and decreases inwards. The plagioclase is frequently dusted with numerous, ultra-microscopic inclusions of some opaque mineral so that it appears brownish, reddish, or purplish under the microscope (MacGregor, 1931). Veinlets of an isotropic material of lower refractive index than the plagioclase traverse the plagioclase crystals and probably represent fused feldspar.

The augite has been converted, partly or wholly, into green chlorite with the separation of small grains of iron ores. Occasionally it has been replaced by uralite and rarely it has been altered to a muddy green biotite.

Near the margins of the sills the olivine has been completely converted either to an indefinite brown serpentinous aggregate /

aggregate or to iddingsite. In parts of the sills far from the margins, small scraps of olivine remain in the centre of the serpentine or iddingsite. In the case of the Monadh Mhiltich sill, much of the olivine in the higher parts of the mass has not been serpentinised; the unserpentinised olivine has, however, been dusted with many minute inclusions of opaque material and the olivine crystals now appear purplish in colour.

The hypersthene has been converted to a pale chloritic material. Magnetite and apatite have not been affected by the metamorphism.

The infillings of the amygdales, occurring in the marginal portions of the sills, have been intensely metamorphosed and converted into green hornblende, cloudy plagioclase, scapolite and numerous, very small, acicular crystals of an unidentified mineral.

The actual contacts of the metamorphosed sills with the surrounding acid rocks are rarely seen, but the rocks in the immediate neighbourhood of the contact are frequently exposed. 'Net-veining' was not found in any of the sills nor were any blocks suggesting veining of the dolerites by the acid rocks found in the screes below the sills. The acid rocks show no modification where they are in contact with the sills.

The /

The contacts of these sills with the granitic rocks are thus markedly different from the contact between the latter and the basic plutonic rocks (see below pp. 159-175).

The unmetamorphosed, but probably pre-granitic sill, which cuts the Torridonian, is a lenticular mass with an outcrop 250 yards in length and 50 yards in breadth; the thickness is 50 feet. The rock is an ophitic olivine-dolerite with zeolite-filled amygdales near its margins. In size and in form this sill closely resemble the seven metamorphosed sills which occur within the acid rocks and is in striking contrast to the post-granitic intrusions.

(ii) DYKES

A number of pre-granitic dykes have been detected within the acid rocks. Like the sills described above these dykes show no 'net-veining' phenomena. They follow slightly sinuous courses which were probably not original. The acid rocks show no unusual features where they adjoin the older dykes. The dykes were originally sub-ophitic olivine-basalts; the metamorphism which they experienced produced results broadly similar to those produced in the sills. A number of differences between the metamorphosed dykes and sills, however, exist.

The augite of the dykes has often been partly recrystallised /

lised to small colourless granules; replacement of the augite by brown hornblende also occurred. The olivine of the dykes was not completely serpentinised, significant proportions of fresh olivine still remain. Large poikiloblasts of brown hornblende were developed in the dykes. In places the dyke rocks were slightly shattered along narrow zones which are now occupied by veinlets of brown augite. Near the shattered belts the metamorphism reached a more advanced stage than elsewhere; the augite recrystallised completely, hornblende became rare and magnetite was formed in abundance.

The pre-granitic dykes have suffered more extensive thermal metamorphism and less hydrothermal alteration than the sills. In particular, the olivine of the dykes is remarkably fresh in comparison to the highly serpentinised olivine of the sills. The sills may have acted as horizontal traps in the path of the rising volatiles thus accounting for the marked hydrothermal alteration of the sill rocks. For their volume the narrow dykes have a large surface area and this may explain their higher grade of metamorphism.

3. THE POST-GRANITIC DYKES AND SHEETS

Approximately 250 dykes and sheets of known or assumed post-granitic age are known to occur in the west of Rhum.

Many /

Many unmetamorphosed dykes and sheets cut the acid rocks (See Plate VI, Fig. 1) and are demonstrably post-granitic. A considerable number, however, cut only the Torridonian Sandstone (See Plate V, Fig. 1) or the basic plutonic rocks and are assumed to be post-granitic in age because of their petrological similarity to the undoubted post-granitic dykes and sheets and the contrast between them and the metamorphosed intrusions. The lavas, which rest unconformably upon the acid rocks and upon the thrust fault forming the northern boundary of the graphophyre, are cut by sparse representatives of the post-granitic swarm.

The post-granitic dykes and sheets are usually less than 5 feet in width, and individual dykes and sheets can rarely be traced for more than a short distance; in some cases the intrusions are seen to die out vertically or laterally and are then replaced by others following the same course but offset by a few yards.

Harker (1908, p. 144) claimed that the dykes of Rhum formed a radial swarm centred near the head of Glen Harris. At least in the west of the island this is not the case. The dykes normally follow courses determined by the joints or other planes of weakness in the surrounding rocks.

Richey (1948, p. 88) suggested that the sheets formed a series /

series of concentrically arranged cone-sheets, but in fact the sheets strike in all directiosn and dip at various angles. No regular arrangement of the sheets has been discerned: the attitudes of the various sheets appear to be determined by the jointing of the surrounding rocks.

The post-granitic dykes and sheets belong to six petrographic groups. The great majority of the intrusions belong to two of these groups viz. ophitic and intergranular basic rocks, which may be either dolerites or basalts. Three other groups viz. porphyritic dolerite and basalt, mugearite-tachylyte, and augite-andesite are each represent by several intrusions. The sixth, represented by a dyke of pitchstone, was reported by Harker (1908, pp. 177-178) who also described the occurrence of pitchstone fragments from other localities. Although the present writer has found pitchstone fragments he has been unable to locate the dyke mapped by Harker.

The petrology of each of the six types is briefly summarised below.

a. and b. Ophitic and Intergranular Dolerites and Basalts. (See Plate XXXVIII and Plate XL, Fig. 1).

These rocks are ophitic and intergranular olivine dolerites and basalts of a type common in the British Tertiary province (Harker, 1904, pp. 321-324; 1908, pp. 152-161; Thomas, 1930, pp. 350-352; Cockburn, 1935, pp. 542-543) and need not be described /

described further. Their margins are frequently tachylytic. (See Plate XL, Fig. 2).

c. Porphyritic Dolerites and Basalts. (See Plate XXXIX).

In these dykes large xenocrysts of plagioclase (An_{80-90}) are set in a groundmass of small plagioclases (An_{65}), granular or sub-ophitic augites and magnetite. Some olivine is present in some dykes and sheets.

The plagioclase xenocrysts are anhedral, almost unzoned and very closely twinned. They are partly chloritised or kaolinised and near the margins of one sheet, are cut by veinlets of isotropic material of lower refractive index than the host crystal. These veinlets appear to consist of glass representing fused plagioclase. In some crystals similar veinlets containing a mineral of slightly lower refractive index and of approximately equal birefringence to the host plagioclase are found. These veinlets probably contain plagioclase which has been fused and recrystallised.

A thin-section cut from a specimen of one of these dykes was examined on the Universal Stage. Two clinopyroxenes, viz., augite-pigeonite ($2V=+54^{\circ}\pm 2^{\circ}$; $Z \wedge c = 33^{\circ}\pm 3^{\circ}$) and clinoenstatite ($2V = +36^{\circ}\pm 4^{\circ}$; $Z \wedge c = 23^{\circ}$) and one orthorhombic pyroxene /

pyroxene viz. enstatite (2V = $\pm 61^{\circ} \pm 3^{\circ}$) were identified in the groundmass of this rock.

d. Mugearite-Tachylyte. (See Plate XXXVIII, Fig. 2).

Two dykes of this type have been encountered on Rhum. No dykes of mugearite-tachylyte have previously been recorded from the island although Harker (1908, pp. 156-161) described several from Muck.

The rock is greenish-grey and traversed by numerous joints. Sparse amygdales filled by quartz or fibrous zeolites occur. The specific gravities of two specimens from one of the dykes are 2.67 and 2.74 respectively. These values are in good agreement with the specific gravities of the mugearite-tachylyte of Muck (2.56-2.72) and of Skye (2.65-2.75) and are in contrast to the specific gravities of basaltic tachylytes from Skye (2.76-2.92) and of the pitchstones of the Small Isles (2.39-2.48).

The matrix of the mugearite-tachylytes of Rhum is a brown, feebly birefringent glass which is normally translucent but is almost opaque in patches and spherules. The refractive index of the glass slightly exceeds that of Canada Balsam (Tilley, 1922; George, 1924). Microlites of partly chloritised augite and of feldspar, often arranged in tufts, lie in /

in this matrix; some of the feldspar microlites have straight extinction whereas others extinguish obliquely. Microphenocrysts of partly chloritised plagioclase (andesine?) occur sparsely. Black ore is present as grains and as many-branched stellate crystals. Relatively large crystals of haematite occur near the amygdales.

The two mugearite-tachylyte dykes of the west of Rhum represent the only known potential source for the flows of mugearite lava.

e. Augite-Andesite. (See Plate XXXVIII, Fig. 2).

Three augite-andesite dykes cut the acid rocks of the west of Rhum. Harker (1908, pp. 164-165) reported dykes of augite-andesite from the southern part of the island but not from the west.

The rocks are brownish and fine-grained and contain sparse chlorite-filled amygdales. Their mineral constituents are plagioclase, augite and magnetite. The bulk of the plagioclase is oligoclase (An_{10-20}) which occurs as subhedral tabular crystals unzoned and rarely twinned. Sparse phenocrysts of a more calcic plagioclase are present in two of the dykes; these phenocrysts are much zoned from a more calcic core to a more /

more sodic margin, highly turbid, and occasionally epidotised. The almost colourless augite forms small granules much altered to brownish chlorite.

One augite-andesite dyke cuts a post-granitic basalt sheet and it is believed that the augite-andesites are younger than the preponderant basaltic and doleritic minor intrusions.

f. Pitchstone.

Harker (1908, pp. 177-178) recorded one pitchstone dyke from Rhum. He described the rock of this dyke as "nearly black, with a vitreous lustre, and without conspicuous crystals". As already mentioned (see above p. 129) the present writer did not find the dyke despite an intensive search in the locality indicated by Harker.

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VIII. THE BASIC PLUTONIC ROCKS OF THE WEST OF RHUM AND THEIR RELATIONSHIP TO THE ACID ROCKS.

THE BASIC PLUTONIC ROCKS OF THE WEST OF RHUM AND THEIR RELATIONSHIP TO THE ACID ROCKS

1. INTRODUCTION

The term 'basic rock' is used throughout this paper in the wide sense to include not only rocks such as gabbro but also harrisite and peridotite which are more usually referred to as 'ultrabasic'. 'Plutonic' is used in a purely descriptive sense to distinguish the large masses of coarse grained rocks from the smaller medium-grained masses. In the Isle of Rhum such basic plutonic rocks underlie a roughly circular area approximately five miles in diameter and thirteen square miles in area. The central part of this area is underlain by peridotite, while gabbro occurs peripherally and also as isolated masses within the peridotite. In the west a mass of harrisite occurs, and in the east almost horizontal sheets of allivalite are interbanded with the peridotite. On the western and northern boundaries respectively, the basic plutonic rocks are in contact with graphophyre and Torridonian Sandstone; on the east they are bounded by a ring-fault while on the south-west their outcrop is cut off by the sea. Elsewhere they are in contact with felsite and supposed Lewisian Gneiss.

The investigation here recorded extended over a narrow strip of basic rocks where they adjoin the graphophyre in the west /

west of Rhum (See Fig. 8). The strip includes, from north to south, part of the main peridotite mass of Rhum, the entire harrisite mass, a mass of gabbro, and, in the extreme south, another portion of the main peridotite. Three of the four main petrographic types of the basic rocks of Rhum are represented in the area under consideration.

The basic plutonic rocks of the west of Rhum form a single petrological unit. No internal contacts were found within the mass of the basic rocks; no recognisable xenoliths of one type were found within another; and no metamorphism of one rock type by another has been detected. The passage from one rock type into another was found to be gently transitional, often over several hundred yards, while the rocks themselves varied considerably even in a single exposure. As a result field mapping of the different types is exceedingly difficult and the division on the geological map of the mass of the basic rocks into areas of gabbro, harrisite, and peridotite represents the general nature of the rocks over these areas rather than the exact spatial distribution of closely defined rock types.

Layering is developed throughout large parts of the basic plutonic rocks, especially in the harrisite and the gabbro. The dips and strikes of the layers remain constant over /

over the entire western part of the basic plutonic rocks, the layers being parallel to the junctions between the various rock types. The lowest part of basic plutonic mass now exposed is the gabbro. In the north the gabbro is succeeded upwards by harrisite which, in turn, is succeeded by peridotite; in the south, however, the gabbro is overlain directly by peridotite without the intervention of harrisite.

2. THE PETROLOGY OF THE BASIC PLUTONIC ROCKS

The petrology of each of the three types of basic plutonic rock in the west of the Isle of Rhum - peridotite, harrisite, and gabbro - will be described commencing with the peridotite, the highest part of the basic plutonic mass now preserved, continuing with the harrisite, and concluding with the gabbro, the lowest part of the basic mass now exposed.

a. PERIDOTITE

The tract occupied by the peridotite is characterised by many small cliffs and rocky knolls separated by almost level areas of peat-covered ground (See Plate I, Fig. 1). Consequently the exposures, although excellent, are irregularly distributed and discontinuous.

The /

The peridotite is a dark green or almost black rock which weathers to a reddish-brown colour. It is traversed by numerous joints which are often regular but are locally irregular. Indistinct layering is frequently seen. The minerals present are, in order of abundance, olivine, plagioclase, augite, iron ores, hornblende, biotite, chlorite and apatite. (See Plates XIII and XIV, Fig. 1).

Olivine forms between 80% and 90% of the normal peridotite but in the north the proportion present locally decreases and may fall to 50%. The crystals, which vary in habit from anhedral to subhedral or even euhedral, have been partly serpentinised along curving cracks. A very notable feature is that the proportion of serpentine present varies directly with that of augite and does not depend on that of olivine, except in so far as the olivine content of the rock limits the proportion of augite which can be present. The significance of this relationship between the proportions of augite and serpentine is not yet understood. The vast majority of olivine crystals show little or no cleavage but a few crystals with one well-developed cleavage can normally be seen in thin section. Frequently very small dendritic inclusions of opaque material are arranged along straight lines within the olivines and where olivine and plagioclase are contiguous reaction rims of augite are occasionally developed.

Plagioclase

Plagioclase is present throughout the peridotite and is normally a highly calcic variety (An_{80-90}). Multiple twinning on (010) and on (001) is general and zoning is especially well-developed in the varieties poor in olivine. The plagioclase occurs interstitially, as large crystals crowded with inclusions of olivine, and as tabular crystals without or with few inclusions. Numerous cracks, presumably caused by the partial serpentinisation of the olivines, traverse the plagioclase. Locally the plagioclase is saussuritised, especially along these cracks.

Pale brown augite is present throughout the peridotite in proportions ranging from traces up to 30%. In chrysophyric rocks the augite occurs interstitially; where olivine falls below approximately 80% it forms large plates with numerous poikilitic inclusions of olivine.

A small proportion of pleochroic brown hornblende commonly occurs in the peridotite, rarely amounting to as much as 5%. It replaces augite and also occurs in association with pale green chlorite, brown biotite, augite, and iron ores as small interstitial patches or as composite inclusions within the olivine crystals.

Ores are common in the peridotite. In sections of chrysophyric rocks they are commonly dark red in thin edges and /

and therefore chromite, but in rocks less rich in olivine they appear to be generally magnetite. The ores, which vary from small euhedral grains to large and anhedral masses, tend to be concentrated in melanocratic parts of the rock. Accessory apatite is also common.

In the northern parts of the peridotite, the rock has locally suffered slight and sporadic alteration from some unknown cause. In the altered parts of the rocks the olivine crystals are seen in thin section to be purplish and dusted by minute opaque inclusions. Fine-grained reaction rims of fibrous augite intervene between olivine and plagioclase, which has been locally altered to scapolite. Even in a single thin section some parts of the rock are almost unaffected whereas others are extensively altered.

b. HARRISITE

The main mass of harrisite in the Isle of Rhum lies in the west of the island and forms a lenticle 2 miles in length, 600 feet thick and of indeterminate breadth. Westwards the harrisite is in contact with graphophyre and gabbro, while eastwards it is overlain by the main peridotite mass of Rhum.

The term 'harrisite' was introduced by Harker (1908a, p. 71) /

p. 71) to denote a rock consisting of "largely preponderant olivine with anorthite and perhaps a little pyroxene, the olivine being of a peculiar black lustrous variety with good cleavage". The type locality for this rock is the mass in the west of Rhum. Tröger (1936) takes as typical harrisite a rock from Dornabac Bridge in the west of Rhum which contains 64% olivine ($Fo_{83}Fa_{17}$), 28% plagioclase ($Ab_{17}An_{81}Or_{02}$), 7% colourless augite, 1% picotite and chromite and occasionally a small propoertion of hornblende. After the examination of many specimens and more than 50 thin sections the present writer considers that <u>typical</u> harrisite consists of about 75% olivine with some bytownite and a smaller amount of pyroxene. The rock is coarse-grained and the feldspar and pyroxene from very large poikilitic crystals which contain numerous olivine crystals. It differs from peridotite in the colour of its olivine in hand specimen, in the presence of numerous olivine crystals with a well-developed cleavage, in the greater grain-size of its olivines (2mm to 10mm) and in the frequent occurrence of bytownite and augite as very large poikilitic crystals. The proportions of bytownite and augite in the harrisite are typically, but not invariably, greater than the corresponding proportions for the peridotite.

The

The harrisite forms a very broken tract characterised by rocky knolls and many small cliffs (See Plate I.). In the west the tract rises to an elevation of some 1,350 feet, in the east the elevation is between 500 and 700 feet. Exposures of the harrisite are good and very numerous, especially in the central parts of the tract. In the north and south of the tract, however, considerable areas are obscured by peat and vegetation.

The harrisite is a black rock which is diversified in appearance by irregular white stringers and patches of plagioclase. Normally it is little weathered except for a reddish-brown crust a few millimetres thick, but locally it is decomposed to a coarse reddish aggregate which is sufficiently incoherent to be quarried and used as 'sand'. Only the coarser parts of the rock (See following paragraph) are affected in this way and the finer parts remain almost unweathered and much impede the quarrying operations.

The harrisite is commonly layered (See Plate II), the layers being alternately relatively fine and chrysophyric and coarse and feldspathic. The direction of dip of the harrisite layers is roughly constant, being to the south and east at angles ranging up to 45°. The surface of the harrisite slopes from west to east at an angle slightly less than the dip of the layers: in consequence the top of the harrisite

is /

is exposed in the east and successively lower horizons are exposed westwards.

An anastomosing plexus of plagioclase veins, varying from threads 0.25mm. in width to bands 100mm. broad, traverses parts of the harrisite (See Plate III, Fig. 1). These veins, which contain subsidiary amount of pyroxene, are usually inclined at approximately 60° to any layering that may be present.

The harrisite consists of 50% to 85% of olivine which occurs as rounded grains partly altered along curved cracks to a pale green serpentine. In varieties relatively rich in augite (e.g. 20%) from 25% to 50% of the olivine has been serpentinised, while in those with a normal (e.g. 10%) or less than normal content of augite the olivine has been converted to serpentine to the extent of only 10% to 30%. The significance of this relationship between the augite content of the rocks and the degree of serpentinisation of the olivines is not understood. Occasionally the olivine has been altered completely to chondrodite or clinohumite. The olivine crystals are usually highly irregular in form and frequently contain very small dendritic inclusions of some opaque mineral. Near the top of the harrisite the olivine has a composition, as determined by measurement of 2V on a Universal /

Universal Stage, of $Fo_{85}Fa_{15}$, near the base the composition, determined similarly, is $Fo_{80}Fa_{20}$. Where olivine and plagioclase are contiguous reaction rims of hypersthene often intervene.

Plagioclase forms from 5% to 25% of the harrisite, and varies in composition from An_{65} to An_{90}, the more calcic varieties predominating. The more chrysophyric varieties of the harrisite tend to have more calcic plagioclase than the feldspathic varieties. The plagioclase occurs as large crystals often crowded with poikilitic inclusions of olivine so that the plagioclase appears to form a series of narrow veinlets between the olivine crystals. Twinning on (010) and (001) is present, many crystals being twinned on both planes, and indefinite zoning is occasionally seen. The twinning is highly irregular and often interrupted. The plagioclase is remarkably fresh as a rule; locally, however, it is slightly kaolinised and rendered turbid, and occasionally it is saussuritised. Slight expansion cracks are found radiating from the olivine crystals.

Clinopyroxene forms from 5% to 30% of the harrisite. $2V = +51^\circ$; $Z \wedge c = 39\frac{1}{2}^\circ$; the clinopyroxene is therefore augite (Winchell, 1948, p. 227). Occasionally schiller inclusions are present.

Hypersthene /

Hypersthene is not common in the harrisite; it is found as reaction rims between olivine and plagioclase. Small grains of magnetite and flakes of foxy-brown biotite are common throughout the harrisite. A little cinnamon brown hornblende is often present. Green epidote, colourless mica, and tremolite are sometimes to be found. The accessory minerals normally form interstitial patches and are usually associated with serpentinous or chloritic material.

Both the layering and the feldspathic veins differ in nature and distribution through the harrisite mass in such a way that it has been found possible to sub-divide the latter into six zones. The zones are approximately tabular and are parallel to the individual layers and to the contact of the harrisite with the overlying peridotite. On the other hand the contact of the harrisite with the graphophyre is oblique to the layering and transgresses from the lower zones to the higher zones in a northward direction. The environment of the harrisite mass in its northern part and the succession of the zones are as follows:-

Peridotite /

Peridotite.

Peridotite traversed by numerous irregular plagioclase veinlets.

HARRISITE	UPPER MASSIVE SERIES	6. Coarse harrisite with irregular feldspathic veins. 5. Pitted harrisite, normally massive but occasionally layered.
	CENTRAL LAYERED SERIES	4. Fine harrisite consisting of many thin layers and cut by almost horizontal feldspathic veins. 3. Coarse harrisite consiting of relatively thick layers and cut by almost horizontal feldspathic veins.
	LOWER MASSIVE SERIES	2. Harrisite, mainly massive but occasionally layered. Feldspathic veins cut obliquely any layering present. 1. Massive harrisite cut by very numerous, highly irregular, feldspathic veins.

Zone of 'net-veining' with basaltic blocks enclosed in aplite.

Graphophyre.

The sequence tabulated above is that encountered on a traverse /

traverse from 100 yards south of Loch an Dornabac to the southern slopes of Ard Nev. Further to the north the granophyre, as already mentioned, transgresses upwards until, in the extreme north of the harrisite mass, it becomes contiguous with the lower part of the Central Massive Series.

The origin of the layers of the harrisite has not yet been satisfactorily elucidated. Although Harker (1908b) mapped the dip and strike of the layers, he did not put forward any explanation of these structures. Wager and Brown (1951), in a short note based on six specimens and a few days field work, suggested that the layering was caused by 'bottom accumulation' in a postulated magma chamber. They maintained that the fine layers were produced by the settling of olivine crystals on the floor of the magma chamber and that the coarse layers were the result of the crystallisation of upward-growing, coralloid olivines. An alteration of conditions in the postulated magma chamber was invoked to explain the alteration of fine and coarse layers.

The present writer objected to Wager and Brown's explanation in a brief note:-

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RHYTHMIC LAYERING IN THE ULTRABASIC ROCKS OF RHUM

SIR,—In the May–June number of the *Geological Magazine*, 1951, pp. 166–8, you publish a preliminary note on recent observations made by Professor L. R. Wager and Mr. G. M. Brown on the " Rhythmic Layering in the Ultrabasic Rocks of Rhum ". I found this note of particular interest as I have been studying the petrology of the south-western part of Rhum, and in particular the harrisite, for the past two years.

According to Wager and Brown, the harrisite was built up from below ; and periods of upward growth of long, branching, coral-like olivines alternated with periods of precipitation and accumulation of discrete olivine grains. Referring to the layered structure, Wager and Brown note " that it will be possible to map individual sheets over wide areas much as a normal series of sedimentary rocks may be mapped ". Later they add : " we are satisfied that the fundamental characteristic of the Skaergaard intrusion, namely accumulation of material from the bottom upwards, is responsible also for the sheet structure of the Rhum rocks." This tacitly assumes that the stratigraphical sequence of the layers is identical with their time sequence, an assumption that cannot be made without the support of evidence based on a thorough investigation of all the contacts concerned. The authors illustrate their interpretation by a photograph of a vertical rock face (Plate VII). This photograph cannot be said to demonstrate the structure described at all clearly as it is the white material (plagioclase) which appears to branch more conspicuously than the grey (olivine). In my own experience, based on field observations and examination of many thin sections, I have found the branching material " growing up " from the base of each layer to be vein-like aggregates of plagioclase, not single crystals of olivine ; the olivine individuals are characteristically nearly equidimensional and subhedral. Throughout the harrisite the plexus of plagioclase veinlets is more resistant to weathering than the olivine and stands out on weathered surfaces in much the same way as granophyric net-veins in basic rocks and with a similar type of pattern. If there are coral-like olivine crystals in the harrisite, such as Wager and Brown describe, they must be quite exceptional ; so far, I have not seen any, though certain granular aggregates of olivine do locally simulate branching forms. Moreover, if Wager and Brown's postulated conditions had obtained, one would have expected an increasing tendency to idiomorphism in the olivines towards the upper part of each layer. In all the examples I have studied I have found no such tendency ; the olivines are everywhere subhedral.

It should be pointed out that Harker long ago noticed the " coralline " structure of some of the layers. In the " Small Isles " *Memoir*, 1908, p. 75, he wrote : " Many of the rock-faces are pitted or even irregularly honeycombed, sometimes with cavities of rudely branching form. The salient parts often have forms resembling ' concretionary growths in impure calcareous or calcareo-argillaceous sediments, or, when more elaborately developed, recall the shapes of sponges and corals. More remarkable structures arise when effects of this kind have been superposed upon a well-marked fine banding. Here we find structures comparable with a certain type from the Magnesian Limestone of Durham, in which the concretionary growth has not obliterated the original lamination." Harker's highly significant analogy serves to emphasize the extreme difficulty of the problem. In the " coralline " layers of the Magnesian Limestone we know what the parental material was and yet have no convincing explanation to account for the structure. In the case of the layered peridotites of Rhum we do not know as yet what the parental material may have been, or even if there was any, other than a hypothetical magma. It is therefore not surprising that there is still no satisfactory explanation for these enigmatic structures.

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16th June, 1951.

Thin-sections cut from specimens of the various zones of the harrisite have been examined and all, with a few exceptions, conform to the petrographic description of the rock given above (pp. 144-146). The specimens differ from each other in granularity and, in some cases, in the proportions of the various minerals present, but they exhibit no significant textural variation.

The specimens which do not conform to the description all occur at the very top of the harrisite mass in the uppermost part of the Upper Massive Series. These rocks are typical harrisites except that they are traversed by narrow veins (See Plates XV and XVI) containing various combinations of the following constituents:- olivine, plagioclase, augite, hypersthene, hornblende, biotite, scapolite, zoisite, magnetite, serpentine, chlorite and glass. The veins traverse the various crystals of the harrisite and their composition is determined largely by the nature of the minerals which form their walls. For example, where the veins cut plagioclase, they are largely composed of granules of plagioclase, scapolite, zoisite, and glass (See Plate XIV, Fig. 2); where they cut olivine they consist mainly of olvimine, augite, hypersthene, magnetite, biotite, serpentine and glass. Hornblende and chlorite are /

are constituents of the veins where they cut augite and are accompanied by olivine, hypersthene, magnetite, biotite, serpentine and glass. That some transport of material along the veins occurred is shown by the presence of plagioclase where the veins cut olivine and augite, and of mafic minerals where the veins cut plagioclase. Very slight displacement (of the order of 0.01mm. or 0.1mm.) has occurred along the veins and in the rocks which contain the veins the twin lamellae of the plagioclases are strongly bent and often broken, and pericline twinning is very common. The displacement is, however, inadequate to support any suggestion that the veins were formed by cataclasis. From the presence of scapolite and zoisite where the veins cut plagioclase it appears to be highly probable that the veins have been formed at the expense of the minerals which form their walls by some process of metamorphism. The widespread occurrence of glass in the veins indicates that some fusion has attended the metamorphism and strongly suggests that the material forming the veins has been produced from the wall minerals by extensive but very localised metamorphism which has frequently resulted in fusion followed by subsequent recrystallisation. The metamorphism and fusion have been probably caused by the passage of hot gases along cracks in the /

the rocks and the veins are therefore analogous to the fused veins cutting plagioclase crystals in the rocks of Slieve Gullion described by Dr. D. L. Reynolds (1952). The veins in the Harrisite differ from the veins described by Dr. Reynolds, however, in that they cut all the minerals of the rock, in that they are developed on a larger scale, and in that the fused material has largely recrystallised.

c. GABBRO

The gabbro occupies a low-lying tract of ground largely covered by raised beach deposits, peat and vegetation (See Plate I, Fig. 1). Exposures are few and are almost entirely confined to two stream sections and a shore section.

The gabbro varies from melanocratic and medium-grained to mesocratic and coarse-grained (See Plate IV, Fig. 1.). Locally small masses of rock sufficiently fine to be termed dolerite occur. These dolerites are irregularly distributed and grade into the normal gabbro; they do not form independent masses but are merely local varieties of the general mass. The term 'gabbro' is for convenience used to include these subsidiary medium-grained rocks.

Layering is developed throughout the gabbro (See Plate III, Fig. 2.). Two types can be distinguished and on this basis /

basis, the gabbro can be divided into an upper and a lower division. The succession across the southernmost part of the gabbro, where the greatest vertical thickness of that rock is exposed, is tabulated below:-

Peridotite.

GABBRO	2.	Massive Gabbro. Inconspicuous layering, the individual layers differing only slightly in composition and granularity.
	1.	Layered Gabbro. Conspicuous layering, the layers being alternately coarse and feldspathic, and fine and rich in olivine and augite.

Zone of 'net-veining' consisting of basaltic rocks in aplite.

Graphophyre.

The boundary between the two zones of the gabbro, the upper contact of the gabbro with the overlying harrisite and peridotite, and the individual layers are all parallel to one another. /

another. The contact of the gabbro with the graphophyre, however, cuts the boundary of the two zones of the gabbro at a high angle, with the result that the graphophyre, which is contiguous with the Layered Gabbro in the south, transgresses upwards towards the north coming into contact with, firstly, the Massive Gabbro and, secondly, with the harrisite, the gabbro here being cut out entirely.

The Massive Gabbro is cut by a widely spaced series of joints parallel to the layering. Several series of joints, also widely spaced, traverse the rock normal to the layers. Weathering has had little effect on the Massive Gabbro.

The Layered Gabbro is cut by several series of joints at right angles to the layering; jointing parallel to the layers is not developed. The fine layers have suffered little change as a result of weathering; the coarse layers, on the other hand, have been frequently converted into a coarse, incoherent aggregate which is quarried for use as 'sand'. Kernels of compact and little weathered coarse rock are frequently found inside this loose aggregate.

The main constituents of the gabbro are olivine, plagioclase, and augite; accessory amounts of hyperthene, biotite, magnetite, and apatite are present. In the Massive Gabbro

and /

and the fine layers of the Layered Gabbro the olivine, plagioclase and augite occur in approximately equal proportions and apatite is rare. In the coarse layers of the Layered Gabbro, on the other hand, plagioclase is roughly equal in amount to that of olivine and augite, and apatite is relatively abundant. Apart from these variations in the relative proportions of the constituents and the occurrence of effects, to be described below, due to contact metamorphism in the coarse layers of the Layered Gabbro, the petrography of the various members of the gabbro mass can be described together.

Olivine normally occurs as interrupted chains of rounded crystals; rarely the crystals are elongated. Partial serpentinisation along curving cracks has occurred and infrequently the serpentine has been converted to opaque indeterminate material. Narrow rims of serpentine often surround the olivine crystals and rows of dendritic inclusions, probably magnetite, occur infrequently within the olivine. Completely serpentinised olivine crystals are found, but only rarely. Occasionally reaction rims of hypersthene or, less commonly, of augite occur between olivine and plagioclase; flakes of brown, pleochroic biotite are sometimes found along olivine-plagioclase boundaries. Rare, crude intergrowths of olivine and augite /

and augite are present.

The plagioclase, An_{55-75}, which forms tabular crystals, is remarkably fresh. Twinning on (010) and (001) is frequent and Pericline twinning also occurs; the twin lamellae are often bent. Slight concentric zoning from a calcic core to a slightly more sodic margin is frequent; oscillatory zoning and irregular and patchy zoning are occasionally developed.

The augite is brown in colour and frequently occurs as large, highly irregular plates including olivine crystals and with a sub-ophitic or non-ophitic relationship to the plagioclase. Occasionally the augite is partly altered to green chlorite.

Hypersthene normally occurs as reaction rims between plagioclase and olivine but occasionally it forms large irregular crystals which contain poikilitic inclusions of olivine. A few hypersthene crystals are schillerised and many of the crystals are partly converted to bastite.

Sparse flakes of biotite, normally brown but occasionally green, occur throughout the gabbro in association with chlorite and magnetite. Small amounts of iron ore are always present and variable amounts of accessory apatite occur.

Locally /

Locally the gabbro is veined by zeolites in association with almost opaque glass. The principal zeolite of these veins has high birefringence, a straight extinction and a positive or negative elongation and is therefore thomsonite; it forms sheaves of acicular crystals and also spherules averaging 0.02 mm. in diameter. The glass forms a significant proportion of the veins and is brown in transmitted light and white by reflected light. Adjoining the veins, the gabbro is altered. The plagioclase has been zeolitised, the augite chloritised and the olivine serpentinised. Secondary quartz and irregular crystals of haematite are found in this altered gabbro.

The coarse layers of the Layered Gabbro have suffered contact metamorphism. The olivine crystals of the coarse rocks contain numerous minute inclusions, which cause the olivines to appear purplish in transmitted light, and they have often been highly serpentinised around their margins. The augites contain numerous inclusions of iron ore and have been partly converted to brown hornblende, brown biotite, or chlorite. The plagioclase has most commonly been replaced by scapolite (with or without accompanying zoisite) and glass; or it has been converted into a yellow chloritic aggregate. Frequently the plagioclase appears brownish or purplish /

purplish by transmitted light, presumably indicating the presence of dispersed ultra-microscopic particles. Where hypersthene was originally present in the coarse layers it has been largely converted to bastite. The magnetite grains are frequently surrounded by a rim of brown biotite.

Areas of extreme alteration consisting of various combinations of serpentine, chlorite, bastite, biotite, hornblende, iron ore, scapolite, zoisite, and glass occur in the metamorphosed rocks. Where augite is contiguous with these patches it has a double reaction rim, the outer part of which consists of brown biotite and the inner of brown hornblende.

The metamorphism is confined to the coarse layers of the Layered Gabbro, the intercalated fine layers being unaffected. The metamorphism increases towards the junctions of the coarse rock with the fine layers. In the field it was observed that thin dykes of the fine gabbro cut the Layered Gabbro and pass continuously into one or other of the fine layers to which they clearly served as the respective feeders. From this evidence it follows that the Layered Gabbro consists of two petrographically distinct units which were emplaced at different times. The coarse layers formed the earlier unit; the fine layers were introduced from depth by means of the almost vertical feeding dykes and were injected along a series of approximately horizontal planes of weakness in /

in the coarse gabbro. The Layered Gabbro is characterised by its lack of joints parallel to the layers and it is probable that the planes of weakness in the coarse rock, along which the fine gabbro was injected, were approximately horizontal joints. The injection of the fine gabbro probably welded these joints so that the entire Layered Gabbro, as it is at present, is devoid of jointing parallel to the layers.

The details involved in the introduction of the fine layers are difficult to elucidate. From the extensive pneumatolytic alteration of the coarse layers it appears that the injection was accompanied by the passage of significant quantities of volatile reagents along the channels now partly represented by the feeding dykes and the fine layers. There is no evidence indicating a significant difference of temperature between the coarse and the fine rocks during the injection, the absence of chilling suggesting that the coarse layers still retained a high temperature when the injection took place. The abrupt nature of the contacts between the fine and coarse layers suggests that the fine rocks were not formed from the coarse rocks, but were introduced from below.

3. THE RELATIONSHIP BETWEEN THE BASIC PLUTONIC ROCKS AND THE GRAPHOPHYRE

The /

The contact of the basic plutonic rocks with the graphophyre is some four miles in length. It follows a roughly semi-circular course in its southern and central parts; in the north it is straight and trends almost due north and south. The contact dips away from the graphophyre at approximately 80° and is marked along its entire length by a strip of hybrid rocks. These hybrid rocks consist of commingled acidic and basic materials; where relatively large basic blocks lie in an acidic matrix they form a strip of typical 'net-veining'. (See Plate 8).. Harker, who first attempted to account for the hybrid rocks, stated (1908a, p. 105) that the acid rocks had intruded the basic rocks so "energetically" that the latter were fragmented; the fragments were incorporated in the acid rocks as xenoliths thus producing "a zone of visible admixture, at one place nearly 50 yards wide, consisting of a kind of <u>intrusion-breccia</u> of dark fragments set in a light matrix. According as one or the other rock predominates, the admixture may be regarded as a network of veins of the later rock traversing the earlier or a crowd of fragments of the earlier enclosed within the later."

Along the greater part of its length the contact zone is poorly exposed. Where it occurs on the shore, however, at Harris and again near the mouth of the Abhainn Fiachanis, it /

it is well and continuously exposed. Other good exposures occur in the Monadh Mhiltich near the northern extremity of the contact.

The hybrid rocks of the contact zone average some 20 or 30 yards in width. The maximum known width is 50 yards and in some places the width of the hybrid rocks is known to decrease to a few feet. The basic fragments occurring in the hybrid rocks are mainly tachylytes, basalts and dolerites; a very small proportion of gabbro is known to occur. The basic plutonic rocks contiguous with the hybrids are peridotite, harrisite and gabbro. The assemblage of fragments does not depend on which basic plutonic rock is in contact with the hybrid rocks but remains constant over the entire length of the contact zone.

A traverse across the hybrid rocks from the graphophyre to the basic rocks shows that two different types of hybrids are present, one composed dominantly of basic material and occurring against the basic plutonic rocks and the other composed dominantly of acidic material and occurring against the graphophyre. The two types grade imperceptibly into each other and into the basic plutonic rocks and the graphophyre respectively. The basic hybrids are the "intrusion-breccia" of Harker and the acid hybrids are what he considered to be xenolithic /

xenolithic granophyre. The rocks of the contact zone will be successively described from the metamorphosed graphophyre which forms the western margin of the hybrid rocks to the metamorphosed basic rocks which form the eastern wall.

a. Metamorphosed Graphophyre.

Where the graphophyre is contiguous to the hybrid rocks it has suffered slight, but distinct, metamorphism. The orthoclase has been rendered unusually turbid, the hornblende has been replaced by chlorite, and rims of pleochroic brown biotite have developed around the magnetite grains. Patches of pale green chlorite occur commonly and quartz pseudomorphs after tridymite are found in the orthoclase.

Locally the graphophyre, by a reduction in the granularity of the various mineral constituents, has been converted into a rock closely resembling the microgranite of western Rhum. This rock can be distinguished from the normal microgranite of western Rhum by the occurrence in it of biotite, quartz pseudomorphs after tridymite, and chlorite pseudomorphs after hornblende.

Very rare aplite veins cut the metamorphosed graphophyre. These veins, which consist almost entirely of granular quartz and orthoclase, are unchilled against the graphophyre which has /

has been considerably metamorphosed in proximity to the veins. The plagioclase has been abnormally kaolinised with separation of quartz, and the micropegmatite has been recrystallised on a finer scale.

b. Acid Hybrid Rocks.

The acid hybrid rocks consist of an aplitic matrix in which lie fragments of graphophyre and small basic 'clots' which are the highly metamorphosed representatives of small fragments of basic rock. The basic 'clots' are present in very small proportions near the contact of the acid hybrids and the graphophyre, but their proportions increase steadily across the contact zone towards the basic plutonic rocks and reach a maximum where the acid hybrids merge into the basic hybrids.

The aplitic matrix consists dominantly of quartz and orthoclase. The quartz occurs as small angular grains and as sparsely distributed large crystals which have been partly recrystallised along cracks. The orthoclase also normally forms small anhedral grains, but sparse large crystals are present in most parts of the rock. The orthoclase is generally slightly kaolinised; occasionally it is so highly kaolinised as to be turbid. It is frequently intimately intergrown /

intergrown with quartz to form a very fine-grained micropegmatite. The small quartz and orthoclase crystals are believed to have been derived by extensive comminution from the quartz and orthoclase of the graphophyre; it is probable that later recrystallisation occurred which in some cases gave rise to fine micropegmatite. The origin of the large quartz and orthoclase crystals is not known; they may be porphyroblasts or they may have been derived from some unknown source.

Oligoclase occurs in the aplitic matrix but in much smaller proportions than quartz and orthoclase. Two types of crystals are present. The first type is large and subhedral or euhedral and contains inclusions of quartz which, in any one plagioclase crystal, frequently have a common optical orientation. This type of oligoclase which is normally unzoned is believed to be porphyroblastic. The crystals of the second type are smaller and anhedral, and are frequently broken. They consist of a turbid, relatively calcic core surrounded by a more sodic, clear margin. A rapid change in the composition of the plagioclase occurs at the boundary of the core and margin. This type of crystal is cut by veinlets of lower refractive index than the host; the material of the veinlets appears to be plagioclase-glass. Replacement /

ment of plagioclase by kaolin and quartz has proceeded along cracks, and rarely calcite is found replacing much of the mineral. The crystals of the second type are believed to have been mechanically derived.

Anorthoclase is found in the acid hybrid rocks only where there is a high proportion of basic material. The anorthoclase forms large porphyroblasts which, in thin section, have rhombic outlines. Small inclusions of quartz and orthoclase are normally present, and inclusions of mafic minerals are frequent.

Graphophyric inclusions form a large part of the acid hybrid rocks. When they are small the fragments are not easily distinguished from the matrix; larger fragments can, however, be more readily perceived. In composition the larger fragments are identical with the metamorphosed graphophyre which bounds the acid hybrid rocks. The smaller fragments consist of fragmented crystals (see p. 164) and coarse micropegmatite. It is probable that some of the fine micropegmatite referred to above (see p. 164) has been produced by the intense metamorphism of coarse micropegmatite fragments, derived from the graphophyre, which has resulted in a reduction of granularity, The graphophyre wall rocks suffered a similar reduction in granularity.

The /

The basic 'clots' found in the acid hybrid rocks are always small and never exceed 2 mm. in diameter. Magnetite always forms a significant proportion of the 'clots' and abundant prisms of apatite are present both in the 'clots' and in the surrounding matrix. Ferromagnesian minerals are normally present, these include augite, either clear and recrystallised or dusted with magnetite, hornblende, often partly replacing augite, and brown biotite. Most frequently only one ferromagnesian mineral is present; 'clots' containing two are not uncommon; very rarely all three are present. In the largest 'clots' turbid, irregularly twinned and zoned plagioclase is present in small amount.

Isolated crystals of hornblende, biotite, augite, magnetite, and apatite occur throughout the matrix of the acid hybrid rocks. These crystals represent very finely fragmented basic material. The comminution of basic rocks would be expected to result in the production of numerous fragments of calcic plagioclase, but no such fragments have been found. It is probable that the plagioclase fragments produced in this way have been converted to oligoclase (c.f. p. 170).

The acid hybrid rocks have been formed by the metamorphism of pre-existing rocks consisting of a mixture of acidic and basic fragments. Some material has been added during the metamorphism.

metamorphism. The extraordinary abundance of apatite in the rocks suggests the addition of P_2O_5 and the occurrence of numerous porphyroblasts of oligoclase and anorthoclase shows the redistribution and probable introduction of Na. During the transformation of basic rock material into basic 'clots' the original calcic plagioclase has largely disappeared. The Na, Al, and Si and some of the Ca probably went to the formation of oligoclase and anorthoclase and part of the balance of the Ca released was probably fixed in the apatite found in and around the basic 'clots'. The mode of disposal of the excess Ca is not known.

The metamorphosed graphophyre contiguous with the acid hybrids contains quartz pseudomorphs after tridymite indicating that the temperature during the formation of the acid hybrids exceeded 870°C.

c. Basic Hybrid Rocks

The basic hybrid rocks consist of an aplitic matrix with a very large proportion of fragments of basic rocks and a small proportion of fragments of graphophyre (See Plates XXIX, XXX, XXXI, fig. 2.). The abundance of basic material increase towards the contact of the basic hybrids with the basic plutonic Rocks.

The /

The basic fragments of the basic hybrid rocks vary considerably in size, the largest being several inches in diameter and the smallest being about 2 mm. across. The smallest basic fragments have been converted into 'clots' identical with those in the acid hybrids; the larger fragments, however, are less altered and different rock types can be distinguished. A few of the basic fragments have been locally derived from the particular type of basic rock adjoining the basic hybrids; the majority, however, are not locally derived and consist of tachylytes, various basalts (including an easily recognisable rock characterised by numerous, very large plagioclase phenocrysts) and ophitic and non-ophitic dolerites. In one locality, where the basic hybrids are contiguous with harrisite, blocks of gabbro, petrographically identical with the gabbro mass which lies below the harrisite, were found. Pyroxene-granulites also occur in the basic hybrids and represent intensely metamorphosed fragments of the other types of basic rock. All gradations between pyroxene-granulites and metamorphosed basalts and dolerites which have suffered no granulitisation are present.

The gabbro fragments mentioned above have been transported upwards through the basic hybrid rocks for a distance of several /

several hundred feet. The blocks of basalt with numerous large plagioclase phenocrysts are similar to several dykes found in the west of Rhum. The blocks, however, were found where exposures are exceptionally good over a considerable area and no dyke of similar rock is known. The blocks must have been derived from some mass of this feldspar-porphyritic basalt either existing in depth or once existing above the present land surface. In either case transport over considerable distances has necessarily taken place.

Without exception, the fragments are of rock types which could be matched with the various basic lavas, dykes and sheets exposed at present on Rhum. They have all been affected by metamorphism, but to varying extents. An approximation to the original mineral composition of the larger fragments can be obtained by consideration of the least metamorphosed members of the series. It appears that all the basic fragments consisted originally of the same minerals, although their proportions of the latter varied considerably. From the evidence given below the original materials appear to have been as follows:-

Plagioclase (?labradorite) was the commonest mineral of the great majority of the fragments and generally formed tabular crystals. Augite was also common; it was a brown variety /

variety and varied from ophitic to non-ophitic in its relationship to the plagioclase. In many of the fragments olivine was present but normally formed noticeably smaller proportions than are characteristic of the gabbro. Magnetite always occurred in the fragments as did accessory amounts of apatite. In some fragments hypersthene may have occurred.

The majority of the fragments have suffered a moderate grade of metamorphism. Considerable changes in their mineral composition have occurred but complete recrystallisation has not taken place. The plagioclase has become zoned from a core as calcic as An_{70} to a margin as sodic as An_{25}, the difference in composition between the core and the margin being greater in large crystals than in small. In some fragments the small crystals are oligoclase and almost completely unzoned whereas the large plagioclases are still highly zoned, from labradorite or andesine to oligoclase. There is often a very rapid change in composition at the junction of the core and the margin. Dispersion of numerous, dust-like, opaque inclusions is common and the plagioclases so affected are reddish or brownish in transmitted light. This "dusting" disappears at a more intense stage of metamorphism and the crystals are then clear. Partial conversion of the plagioclase to kaolin or sericite is common.

The augite, where metamorphism has been only slight, has been /

been partly or wholly converted into a pale green chlorite with the separation of magnetite, or has become crowded with inclusions of magnetite, many of which are surrounded by a rim of biotite. With increasing metamorphism the augite has been partly or wholly replaced by either a pale green uralite or a brown hornblende. At a still higher stage of metamorphism the augite has been recrystallised as pale, equidimensional granules.

Hypersthene is of restricted occurrence in the basic fragments; where it does occur it appears to have undergone much the same series of alterations with progressively increasing metamorphism as did the augite. Where olivine was present in the basic fragments it has been completely converted to serpentine. The magnetite of the basic fragments is frequently rimmed by biotite as a result of the metamorphism but has been otherwise unaffected; the apatite remains unchanged.

Some fragments have experienced extreme metamorphism and have been completely recrystallised to pyroxene-granulites with the loss of all their former textures. Such rock now consists of granules or tabular crystals of clear and almost untwinned oligoclase, granules of pale augite and grains of magnetite /

magnetite often with biotite, rims, and accessory prisms of apatite. These pyroxene-granulites are not common and, where they do occur, are frequently accompanied by less metamorphosed fragments; all stages from well-developed pyroxene-granulites to slightly granulitised sub-ophitic dolerite occur in one large hand specimen.

The graphophyre fragments and the aplitic matrix of the basic hybrid rocks are identical with those of the acid hybrids, but are present in much reduced proportions. They are presumably of similar origin to the matrix and the graphophyre fragments of the acid hybrid rocks.

The basic hybrid rocks are highly metamorphosed fragmental rocks, the fragments being derivatives from a number of different types of basic rocks. Representatives of some of these rock types are at present exposed in the basic plutonic masses of Rhum. The remaining rock types appear to have belonged to hypabyssal or effusive masses. Some of these are presumably represented by the dykes and sheets found traversing the plutonic rocks. The others are of unknown derivation.

A few of the basic fragments in the basic hybrid rocks have glassy margins which can only have been produced by peripheral fusion of the fragments (See Plate XXXIII). The existence /

existence of these fused margins shows that the temperature attained during the metamorphism of the basic hybrids was extremely high; probably of the order of 1,000°C.

The conversion of the plagioclase of the basic fragments, originally labradorite, to oligoclase demonstrates that the basic hybrid rocks have been enriched in Na. Ca has been released and has probably been fixed in the recrystallised augite. It is possible that P_2O_5 has been introduced into the basic hybrids and has fixed some of the Ca but no definite evidence for this is available. A comprehensive quantitative investigation of the metasomatism which affected the basic hybrids has not yet been made but will be commenced shortly.

d. Metamorphosed Basic Rocks

The basic rocks contiguous with the basic hybrids were originally typical gabbro, harrisite, and peridotite, but they have suffered considerable metamorphism concomitantly with the formation of the hybrid rocks.

The plagioclase of the metamorphosed basic rocks is concentrically zoned from a calcic core (labradorite) to a sodic margin (oligoclase). The margins are kaolinised and turbid and the cores are clear and fresh; there is a rapid change of composition at the junction of the core with the margin. /

margin. Minute opaque inclusions frequently dust the plagioclase which is rendered purplish in colour. Occasionally the plagioclase has been converted into granules of oligoclase and, though rarely, scapolite has also been produced. Highly repeated twinning is present; often the twinning is irregular and commonly the twin-lamellae are bent.

The augite is commonly converted either into uralite or wholly or partly into green chlorite. Where the original augite remains, it contains inclusions of iron ore which are locally so abundant as to render the augite almost opaque, Commonly the augite has been partly replaced by brown hornblende, a single crystal of augite being converted to a single crystal of hornblende; occasionally a fibrous green hornblende has been developed from the augite.

The olivine has been converted almost entirely to colourless antigorite or to yellow iddingsite. Reaction rims of granular hypersthene between olivine and plagioclase are rae, but are well developed when they do occur.

Flakes of brown or deep red biotite are very common in the metamorphosed basic plutonic rocks and apatite is abundant. Here and there parts of the rock have suffered sporadic granulation and have been converted into fine-

grained /

grained aggregates of brown hornblende, olivine, augite and plagioclase; these granular patches are very similar to the rocks of some of the fine-grained veins which cut the uppermost part of the harrisite mass (See above pp. 150-2).

The metamorphism of the basic plutonic rocks by the formation of the hybrid rocks has been accompanied by an introduction of Na which has been fixed in the plagioclase. A small part of the Ca released from the plagioclase has partly combined with the considerable amounts of P_2O_5 which have been introduced and has formed apatite. The remainder of the Ca has possibly joined the migrating material passing through the hybrid rocks. Water has been introduced into the metamorphosed basic plutonic rocks, as is shown by the presence of large proportions of minerals bearing the hydroxyl group. That other volatile substances have also been added is indicated by the presence of small but significant amounts of scapolite.

4. CONCLUSIONS

The original hypothesis that the hybrid rocks found between the acid rocks and the basic plutonic rocks are an "intrusion-breccia" is clearly inconsistent with the evidence /

evidence now available. The acid rocks were formed metasomatically; both the acid rocks and the basic plutonic rocks were metamorphosed during the formation of the hybrid rocks; it can be demonstrated that the basic fragments in the hybrid rocks were not produced by the 'stoping' of the basic plutonic rocks, (See Plates XXIX - XXXII). A new hypothesis for the origin of the hybrid rocks must now be sought. The relevant data will now be summarised:-

The hybrid rocks do not occur where the acid rocks are in contact with pre-granitic basic rocks - they are not found where the acid rocks are contiguous with the metamorphosed basic sills and dykes (See above pp.125-6)-but are confined to a strip between the graphophyre and the basic plutonic rocks. The hybrid rocks contain fragments derived not only from the basic plutonic rocks but also from the graphophyre. Both the fragments they contain and the rocks on either side have been metamorphosed. Accordingly it is seen that the hybrid rocks are younger than both the basic plutonic rocks and the acid rocks which they adjoin.

Some of the material of the hybrid rocks has been transported over considerable distances. The hybrid rocks have been formed at a very high temperature as is demonstrated by the fused margins of some of the basic fragments, the /

the occurrence of veins of plagioclase-glass cutting the plagioclase of the acid hybrids and of the aplitic matrix of the basic hybrids, and the occurrence of quartz pseudomorphs after tridymite in the graphophyric fragments and wall rocks. The hybrid rocks form an almost vertical body of rocks, some 4 miles in length and some 20 or 30 yards in average breadth; they have suffered the addition of a very small percentage of various constituents. From these facts it appears that the hybrid rocks are fragmental deposits which have been metamorphosed by streams of exceedingly hot gases rising from the depths. These gases enriched the hybrid rocks in Na, water, and small quantities of other consitituents and probably derived much of the fragmental material of the hybrid rocks from the wall rocks.

The hybrid rocks form a narrow curving strip; before their emplacement the acid rocks abutted on to the basic rocks along an almost vertical plane. The parental material of the acid rocks - Torridonian Sandstone - abuts at present on to basic rocks in the east of Rhum, the actual contact being marked by a major fault. Along this fault it is known that gases passed upwards and formed hybrid rocks (See pp.75-95); these hybrid rocks differ from the hybrid rocks in the west of Rhum in that the fragments they contain are /

are much smaller and in that they are developed only locally along the fault. The hybrid rocks of the west of Rhum have, in all probability, also been developed along a fault plane by the passage of hot gases. These gases have formed hybrid rocks along the entire length of the fault plane. In places the gases were very active and produced a relatively broad belt of hybrid rocks, while in other places gas activity was less vigorous and only a narrow strip of hybrid rocks was produced. It is probable that the fault-breccia, now replaced by the hybrid rocks, supplied many of the blocks now found in the hybrid rocks.

The southern and central parts of the strip of hybrid rocks mark the original course of the semi-circular fault which separated Torridonian Sandstone or its metasomatised equivalent - the acid rocks - from the basic plutonic rocks. This fault is closely comparable with the ring-fault now found in the east of Rhum which separates Torridonian Sandstone from the basic plutonic rocks and along which hybrid rocks have been locally developed. This analogy suggests that the semi-circular faults found in the east and the west of Rhum are perhaps parts of a once continuous ring-fault which encircled what is now the central part of Rhum. If this should be the case the probable connection of the two parts in the north would be expected to run through an area which has /

has not yet been fully investigated; in the south the two parts are separated by the sea.

The northern part of the strip of hybrid rocks is straight and trends almost due north and south. Here the hybrid rocks have probably been developed along an almost straight fault which, at its southern extremity, joined the ring-fault tangentially; a similar fault is known in the east of Rhum. The hybrid rocks are last exposed some 800 yards to the south of the northern extremity of the contact between the graphophyre and the basic plutonic rocks; further to the north the basic plutonic rocks are in contact with Torridonian. The contact between the basic plutonic rocks and the Torridonian is still under investigation and it is not yet known with certainty whether the fault which separates the graphophyre from the basic plutonic rocks continues past the north-western extremity of the graphophyre and constitutes the contact of the basic plutonic rocks with the Torridonian. The occurrence of a rock consisting of basic fragments set in a quartzo-feldspathic matrix suggests that the fault does continue and indicates that another series of hybrid rocks is developed along the fault between the Torridonian and the basic plutonic rocks.

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5. REFERENCES

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APPENDIX A.

THE JUNCTION BETWEEN JURASSIC SANDSTONES AND TERTIARY GRANOPHYRE NEAR DUNAN, ISLE OF SKYE; A RE-INTERPRETATION.

THE JUNCTION BETWEEN JURASSIC SANDSTONES AND TERTIARY GRANOPHYRE NEAR DUNAN, ISLE OF SKYE: A RE-INTERPRETATION.

1. INTRODUCTION.

The granophyre of the Red Hills in the Isle of Skye is bounded along part of its eastern contact by Jurassic sandstones. The contact, which dips eastwards at about 35°, extends from Loch na Cairidh southwards for two miles until it is truncated by an east-west fault. On the shores of Loch na Cairidh, near the village of Dunan and some 12 miles south of Portree, the contact is well exposed and has been described by T.C. Day(1931) who inferred that veinlets of what would now be called rheomorphic sandstone had intruded the granophyre. Eight new chemical analyses were given by Day and he concluded from these that, in the neighbourhood of the granophyre, the sandstone had been enriched in Al, Na, K, Fe, and Ti, so that it approached the granophyre in composition.

Day's thin-sections and analyses have been re-examined and the conclusion now reached is that the contact is a fault-junction along which mylonites and porphyroclastic flinty crush rocks have been developed. These cataclastic rocks /

rocks very closely resemble those found by the present writer along the granophyre-sandstone contact in the west of the Isle of Rhum.

2. PETROLOGY.

a. Sandstones. (Day's specimen S.8)

A hundred feet from their contact with the granophyre, the sandstones of the Inferior Oolite are light-coloured, irregularly-jointed rocks, consisting of quartz and orthoclase with small amounts of microcline and plagioclase and sparse grains of other minerals. The rock is well sorted and the granularity, as seen in thin section, is approximately 0.2mm.. A small quantity of biotite is present and, as the rock seems to be slightly indurated, it is probable that the sandstone has experienced a slight degree of contact metamorphism. The presence of a few shatter veins consisting of comminuted quartz grains with undulose extinctions and small orthoclase fragments suggests that the sandstone has been slightly crushed.

b. Granophyre. (Day's specimens S.1, S.2, and S.9)

The granophyre is a medium-grained leucocratic rock consisting of quartz and orthoclase (largely intergrown), oligoclase /

oligoclase, hornblende, biotite, epidote, iron ores, and apatite. Although Day's specimens were collected near the contact they very closely conform to Harker's description of the Red Hills granophyre (1904, pp. 126-131, 152-164.). However, in Day's specimens there are a few plagioclase crystals with bent or broken twin lamellae and many of the quartz grains show undulose extinction.

c. Cataclastic Rocks.

Six of Day's specimens - those numbered S.3, S.4a, S.4b, S.5, S.6 and S.7 - are of cataclastic rocks. In hand specimen they show well-developed slickensides and are traversed by numerous irregular joints. S.3 is a shattered granophyre which occurs within the normal granophyre to the west of the main fault zone. S. 4a and S.4b are porphyroclastic flinty-crush rocks and come from the western part of the fault zone and the remaining three specimens (S.5 S.6, and S.7) are mylonites occurring in the eastern part of the fault zone between the flinty-crush rocks and the sandstone.

i. Shattered Granophyre. (Day's specimen S.3)

This specimen of otherwise normal granophyre is traversed by veinlets of comminuted material. These veinlets contain angular cataclastic fragments, mainly of strained quartz but occasionally of micrographic intergrowth or of orthoclase, set in /

in a finer matrix of the same minerals. Grains of magnetite and flakes of chlorite are also present in the matrix. The veinlets pass laterally into the normal granophyre.

ii. Mylonites. (Day's specimens S.5, S.6 and S.7)

The mylonites consist of a pale green or cream coloured matrix with numerous fragments and porphyroclasts and traversed by irregular white veinlets. The fragments are of granophyre, the porphyroclasts comprise quartz, micropegmatite, orthoclase and plagioclase, and the finely comminuted matrix consists of the same minerals. The quartzes and many orthoclases have undulose extinction, small fragments can be seen half-detached from large porphyroclasts, and the twin lamellae of the plagioclases are often bent. Under crossed nicols many of the apparent porphyroclasts are seen to be aggregates of very small crystals. The degree of comminution of the matrix is not constant, for, while in some parts of the rocks relatively large fragments predominate, in others only exceedingly small particles are present. In the latter case the matrix is sometimes traversed by veinlets of brown glass.

iii. Porphyroclastic Flinty-Crush Rocks. (Day's specimens S.4a and S.4b)

These rocks have a cherty appearance in hand specimen and are cut by numerous irregular joints. They consist of granophyre /

fragments and numerous porphyroclasts of quartz, micropegmatite, and orthoclase set in a brown glassy groundmass. Although the fragments and porphyroclasts appear in ordinary light to be little affected internally, under crossed nicols they are seen to have recrystallised as numerous small grains. Occasionally the margins of the porphyroclasts have been fused.

3. CHEMICAL ANALYSIS.

In his paper Day published eight new chemical analyses. One of these (Sx) relates to a Great Estuarine Sandstone from a locality some 18 miles from the Inferior Oolite outcrops of Dunan and is not considered here. Another (S.9) shows a serious discrepancy between the sum of its constituents and the total as published. The original copy of this analysis, as set out in Day's laboratory notebook, differs from the published version in that the percentage of Al_2O_3 is given as 12.52 and not as 15.52. The latter figure appears to be a misprint for, when Day's original figure is substituted, the discrepancy between the sum of the constituents and the published total disappears. The corrected analysis has been used in this paper. Of the remaining six analyses, one (S.1) is of granophyre, one (S.8) of slightly shattered /

shattered sandstone, and four (S.3, S.4, S.6 and S.7) are of the cataclastic rocks.

The cataclastic rocks are close to the granophyre in their content of Si, Al, Na, K, and many minor constituents. (Table 5). The amounts of Fe, Mg, and Ti reach their maxima in the cataclastic rocks.

4. CONCLUSIONS.

The contact between the granophyre and sandstone, exposed on the shore near Dunan, was regarded by Day as intrusive but is now shown to be faulted. The rocks between the granophyre and the sandstone are not products of contact metamorphism, as Day believed, but are cataclastic and include mylonites and porphyroclastic flinty-crush rocks. From the chemical data given by Day the cataclastic rocks are seen to be richer in Fe, Mg, and Ti than either the granophyre or the sandstone.

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TABLE 5

	I	II	III
SiO_2	73.77	74.89	84.37
Al_2O_3	12.93	11.79	8.21
Fe_2O_3	1.22	0.85	0.00
FeO	1.48	2.14	0.74
MgO	0.19	0.49	0.24
CaO	0.79	0.67	0.33
Na_2O	3.99	3.77	3.20
K_2O	4.81	4.00	2.60
H_2O + 105°C.	0.47	0.96	0.41
H_2O - 105°C.	0.25	0.19	0.08
CO_2	0.38	0.11	0.06
TiO_2	0.25	0.32	0.14
P_2O_5	0.04	0.04	trace
MnO	0.08	0.06	0,01
FeS_2	0.12	0.20	0.18
	100.77	100.48	100.57

I Average of analysed granophyres immediately to the west of the cataclastic rocks. (Average of Day's analyses of specimens S.1 and S9)

II Average of analysed cataclastic rocks. (Average of Day's analyses of specimens S.3, S.4, S.6 and S.7).

III Sandstone, slightly shattered, immediately to the east of the cataclastic rocks. (Day's analysis of specimen S.8).

APPENDIX B.

AN EXAMINATION OF THE TERMS

"MYLONITE": "FLINTY CRUSH ROCK": "PSEUDO-TACHYLYTE"

AN EXAMINATION OF THE TERMS "MYLONITE": "FLINTY CRUSH ROCK": "PSEUDO-TACHYLYTE"

INTRODUCTION.

In April 1950, the present writer, in the course of an examination of the contact of the granophyre and Torridonian Sandstone in the western part of the Isle of Rhum, found strong evidence that the contact, along much of its length, was not intrusive, as had previously been thought (Harker, 1908), but faulted. Investigation of the rocks in the contact-zone revealed the presence of mylonite and flinty crush rock. The writer took steps to see if these terms, and also the term pseudo-tachylyte, had been given exact meanings and discovered a considerable variation in their definition and usage.

THE DEFINITIONS.

The term "mylonite" (or milled rock) was suggested by Lapworth in 1883 (see Teall, 1921) for certain rocks in Sutherland, which he had recognised as being products of dynamic metamorphism caused by earth-movements. He adopted the term "mylonite" for rocks representing "the extreme phase of mechanical metamorphism".

By /

By 1907, when the North West Highlands Memoir (p.250) was published, a new term - "flinty crush rock" - had come into use for cataclastic rocks which had apparently undergone partial fusion. Although the date of the first use of this term has not been traced, the term is generally ascribed to Clough who, as early as 1888, had described small occurrences of such a rock in the Cheviot area as "flinty-like streaks".

In 1914 a further new term, "pseudo-tachylyte", was used by Shand (1916) to designate a black, glassy, microlitic rock which occurs as veins ramifying through the Parijs granite, in the Orange Free State. These veins he described as the product of rock-melting, and he suggested that they may have been produced by sudden shocks or by gas-fluxing directed along cracks. The production of pseudo-tachylyte was therefore not definitely ascribed to dynamic metamorphism.

INTER-RELATIONS OF THE DEFINITIONS.

Each of these definitions in itself presents difficulty: when they are used to differentiate rocks occurring together they may be confusing.

It seems likely that when Lapworth suggested the term "mylonite" /

"mylonite" he had in mind: (a) pulverised rocks produced by mechanical metamorphism, (b) the particular rocks he wished to describe. The relation of the first to the second is that of genus to species. It is unfortunate that in erecting his species, mylonite, he used the expression "the extreme phase of mechanical metamorphism". Since his day, more extreme phases of mechanical metamorphism have been recognised (e.g. involving fusion); and it is a debatable point whether these should be regarded as new species (Shand, 1950), or as sub-species of "mylonite".

Flinty crush rock connotes one of these more extreme phases of mechanical metamorphism, and, as such, it may be classes as a sub-species of mylonite. This rock, however, is produced by mechanical forces which have induced not only mechanical effects but also vitrifaction. If, therefore, it is assumed - and, historically, the assumption is justified - that Lapworth was considering only rocks which resulted from extreme comminution alone, then flinty crush rock may reasonably rank with mylonite as a species in its own right.

Pseudo-tachylyte is not formed by simple dynamic metamorphism alone but appears to be the product of a combination of processes such as gas-fluxing and sudden shocks. Its microlitic /

litic structure is presumably due to extensive fusion[1], followed by recrystallisation. Whether this possible distinction between flinty crush rock and pseudo-tachylyte is always valid is not clear. The presence or absence of any considerable degree of recrystallisation is not mentioned in the accepted definitions of flinty crush rock (Quensel, 1916, p.104; Holmes, 1920, p.164; see also Waters and Campbell, 1938, p.479); and thus arises a possible confusion in the use of the two terms. On the other hand, while flinty crush rock is a specific result of dynamic metamorphism, pseudo-tachylyte results from other processes. This fact may lead us to consider flinty crush rock and pseudo-tachylyte as independent rock species which may be structurally similar, but genetically different. Thus the definitions themselves lack objective precision, and this must lead to a confusing variety of interpretation and usage

1. Some authors (Hawkes, 1929; Larsen and Bridgman 1938) have attributed the production of pseudo-tachylyte to vitrifaction without fusion. They postulate that the vitrifaction is caused by intense shearing and followed by recrystallisation.

INTERPRETATION AND USAGE.

The terms "mylonite", "flinty crush rock", and "pseudo-tachylyte" are rarely defined (Quensel, 1916, pp. 99-100, 104; Holmes, 1920; Waters and Campbell, 1935) although they are used by different writers with varying interpretations. Even Peach and Horne (1930, pp.40, 44, 51) never decided whether flinty crush rock was a sub-species of mylonite or not.

Where flinty crush rock occurs on a large scale, as in the Outer Isles, it has usually been clearly distinguished from mylonite. (Jehu and Craig, 1923-34.) In the North West Highlands, on the other hand, mylonite is much more common than flinty crush rock, and the former term is normally used in a broad sense to include the latter. (Peach and Horne, 1907.)

Since 1914 some writers have described microlitic rocks of cataclastic origin as flinty crush rock and not as pseudo-tachylyte. Thus Dougal (1924) described and figured a partly recrystallised glassy product of dynamic metamorphism, found in the Isle of Lewis, as a normal flinty crush rock. Of the writers who follow Shand in the use of pseudo-tachylyte, some (e.g. Crickmay, 1933; Harker, 1950,) restrict the term to occurrences of intrusive appearance, while others (e.g. Tyrrell /

Tyrrell, 1949) use it indiscriminately for all partially recrystallised glasses of ultra-cataclatic origin, whether apparently intrusive or not.

In some cases where an attempt is made to discriminate between pseudo-tachylyte and flinty crush rock, large scale occurrences are described as flinty crush rock, while small scale occurrences are referred to as pseudo-tachylyte. (Jehu and Craig, 1923-34).

CONCLUSIONS.

It is clear that there is little accord in the use of the terms "mylonite", flinty crush rock", and "pseudo-tachÿlyte". It is thus obviously desirable that some attempt to establish uniformity should be made. The finely comminuted purely cataclastic rocks can be readily divided into two catagories:-

a. Rocks in which fusion has not taken place.

b. Rocks which have suffered partial fusion without recrystallisation, but which may have undergone much delayed devitrification, and rocks in which the comminuted material has not only been largely fused but in which partial or total recrystallisation has /

has taken place on subsequent cooling.

Consideration of priority of usage leads the present writer to suggest that the term "mylonite" be used for rocks of the first category and the term "flinty crush rock" for rocks of the second category. "Pseudo-tachylyte", in the opinion of the present writer, should be used for microlitic rocks of doubtful origin.

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PLATES.

PLATE I.

Fig. 1. View from near the mouth of the Abhainn Rangail looking north-west. The left foreground is occupied by gabbro covered almost entirely with superficial deposits; the right foreground is underlain by peridotite. Ard Mheall, the rugged hill in the centre, is composed of harrisite. The rounded hills in the background are part of the granophyric and microgranitic tract.

Fig. 2. The south-eastern face of Ard Mheall. The layering in the harrisite, which forms the hill, dips gently towards the right of the photograph. A conspicious feature, possibly a fault, slopes at about 30° to the left.

PLATE I

Fig.1

Fig.2

PLATE II.

Fig. 1. An exposure of harrisite to the north of Loch an Dornabac. To the right the rock is regularly banded, the bands being alternately feldspathic (light) and chrysophyric (dark). On the left homogeneous harrisite dips under the banded material, the junction being parallel to the banding.

Fig. 2. Finely banded harrisite on the eastern face of Ard Mheall. The rock surface is approximately 6 feet by 9 feet. Differential weathering has attacked the chrysophyric bands and has left the feldspathic outstanding. Two series of prominent joints cut the banding at angles of 60° and 70°.

PLATE II

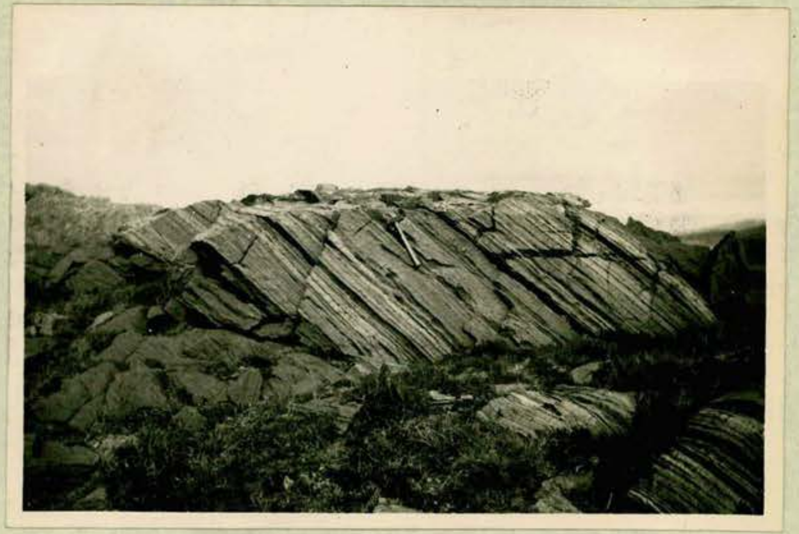

Fig.1

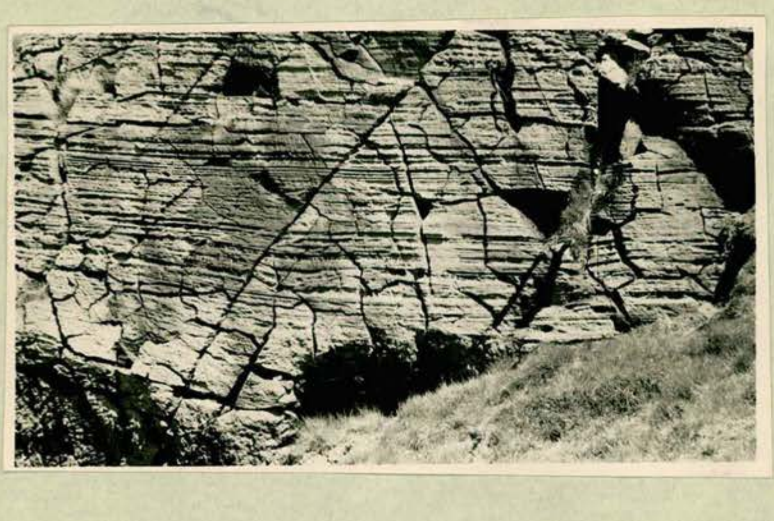

Fig.2

PLATE III.

Fig. 1. An exposure of harrisite from the eastern face of Ard Mheall. The rock is highly chrysophyric and is traversed by a plexus of feldspar veinlets. The chrysophyric material has been preferentially weathered leaving the veinlets outstanding.

Fig. 2. Banded gabbro exposed in the gorge of the Glen Duian River immediately above the bridge near Harris. The rock is highly decomposed; kernels of solid rock occur in the finer bands, the coarser bands are completely decomposed. Feldspathic veins have been emplaced along small reverse faults.

PLATE III

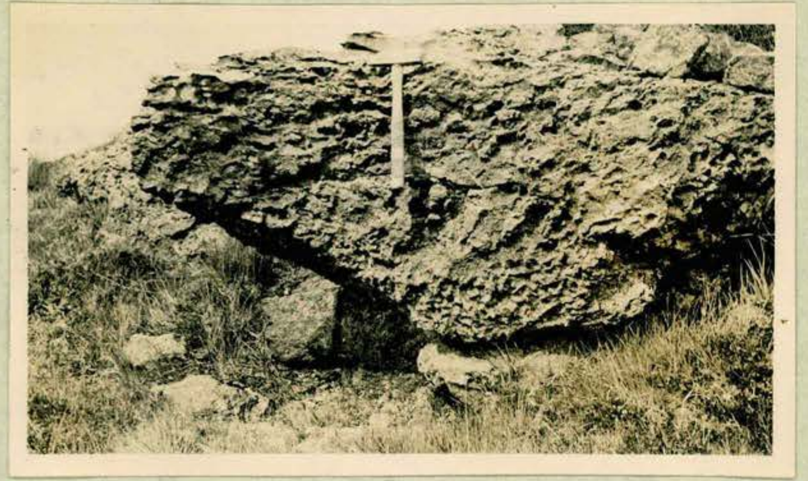

Fig.1

Fig.2

PLATE IV.

Fig. 1. Pegmatoid gabbro on the shore south of Harris. The part shown measures approximately 8 feet by 6 feet. Olivine and plagioclase crystals up to several inches in length can be clearly seen.

Fig. 2. Monocline in Torridonian Sandstone exposed in a sea-cliff ¾ mile north east of Guirdil.

PLATE IV

Fig.1

Fig.2

PLATE V.

Fig. 1. Torridonian arkoses of the Applecross Group seen in the sea-cliffs to the north west of the Allt Camas na h-Atha. These steeply dipping rocks have been affected by the large thrust fault up which the graphophyre has been thrust over the Torridonian. Numerous irregular basaltic dykes cut the strata. The Tertiary Plutonic Complex of the Cuillin Hills of Skye can be seen in the background.

Fig. 2. Part of the tract occupied by the acid rocks as seen from the southern spur of Sron an t-Saighdeir looking east-north-eastwards to Orval. The microgranite occupies the foreground and the graphophyre the background. The superficial cover of loose blocks and vegetation, typical of the area underlain by the acid rocks, is well shown in this photograph.

PLATE V

Fig.1

Fig.2

PLATE VI.

Fig. 1. Graphophyre cliffs on the shore near Harris cut by numereus basalt dykes and veins. The inlet in the foreground has been eroded along two small faults. The prominent ledge is a remnant of the 50-foot raised beach.

Fig. 2. Sea cliffs, 700 feet high, to the south of Wreck Bay. The rock is microgranite the columnar jointing of which is clearly shown. At the base of the cliffs lies the platform of the 50-foot raised beach.

PLATE VI

Fig.1

Fig.2

PLATE VII.

Fig. 1. Cliffs at the Camas na h-Atha seen from the north. Those on the left are of Torridonian Sandstone, those on the right of microgranite. The vertical gully in the centre has been eroded along the line of the important tear fault which extends from Camas na h-Atha to Wreck Bay with a probable south-eastwards continuation parallel to the south-western coast of Rhum. The Allt Camas na h-Atha drops into this gully over a waterfall approximately 100 feet in height.

Fig. 2. A view looking north west down the gully eroded along the tear fault (See Fig. 1.) showing the upper part of the waterfall of the Allt Camas na h-Atha. The left wall of the gully is composed of microgranite, the right of Torridonian Sandstone. The western wall of the fault has moved north-westwards for a distance of $\frac{3}{4}$ mile relative to the eastern wall.

PLATE VII

Fig.1

Fig.2

PLATE VIII.

Fig. 1. Net veining exposed in the sea-cliffs near the mouth of the Abhainn Fiachannis. Dark blocks of basalt are contained in an aplitic matrix. The foreground is of graphophyre.

Fig. 2. Net veining near the locality of Fig. 1. Here the basic material is in excess and is traversed by an almost rectangular system of aplitic veins which are cut by the jointing. ~~of the basic material~~

PLATE VIII

Fig.1

Fig.2

PLATE IX.

Fig. 1. Ard Nev from the south west. The so-called 'Lewisian Gneiss' forms the summit of the hill and rests on the Tertiary graphophyre. The dark lenticle of gabbro, directly below the summit, is contained in and metamorphosed by the graphophyre.

Fig. 2. Fluviatile volcanic conglomerate exposed in the northern face of West Minishal. The blocks are mainly basaltic, but with an admixture of other rock types, and are set in a highly decomposed matrix derived from basalt.

PLATE IX

Fig.1

Fig.2

PLATE X.

Orval from the east.

Fig. 1. An outlier of the Upper Basalt Lavas forms the high ground and rests unconformably on the graphophyre which underlies the foreground and the middle distance.

Fig. 2. The eastern face of Fionchra. The hill is an outlier of Tertiary volcanic rocks resting unconformably on Torridonian Sandstone and on graphophyre. The small escarpments in the upper part of the hill are formed by the Upper Mugearite lava flows.

PLATE X

Fig.1

Fig.2

PLATE XI.

Fig. 1. The north western face of Orval showing the cliff-bound lava outlier resting on the graphophyre which forms the summit of the hill on the right. Large blocks of basalt, derived from the cliffs above, are strewn over to the lower slopes of the hill.

Fig. 2. Fionchra from the west. The prominent escarpment below and to the left of the summit is formed by the Lower Mugearite Lava.

PLATE XI

Fig.1

Fig.2

PLATE XII.

Fig. 1. The seaward face of Bloodstone Hill. The Upper Mugearite Lavas form the upper part of the cliffs and rest unconformably on the steeply dipping Torridonian Sandstone below. The cliffs here exceed 1,000 feet in height.

Fig. 2. Kinloch Glen looking eastwards. This U-shaped glaciated valley cut in the Torridonian Sandstone is partially crossed by two terminal moraines (dark in the photograph) formed during the retreat of the local glaciers in the final stages of the Pleistocene glaciation.

PLATE XII

Fig.1

Fig.2

PLATE XIII

Peridotite
(See pp. 138-141).

Fig. 1. 600 yards E. of the summit of Minishal. Numerous partly serpentinised olivine crystals are enclosed in a large crystal of calcic bytownite and a large augite. One olivine, in the centre of the field, is almost euhedral and shows cleavage. (See pp. 138-141). Ordinary Light. x 17.

Fig. 2. 950 yards S.E. of Dornabac Stables. This rock is approaching a dunite in composition; it consists of partly serpentinised olivine with a little chromite and a small proportion of turbid plagioclase (lower left of the field). (See pp. 138-141). Ordinary Light. x 17.

PLATE XIII

Fig.1

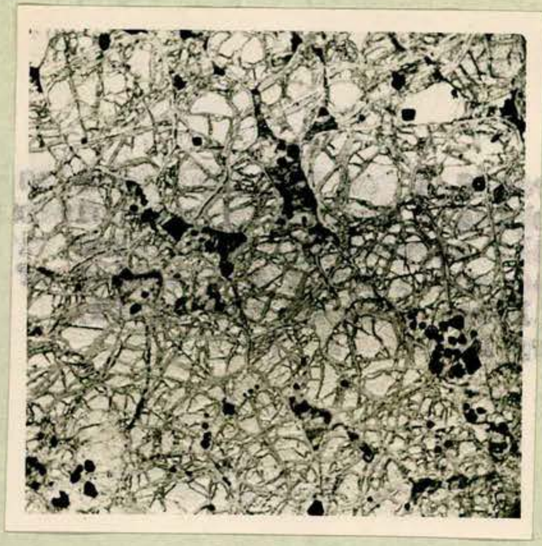

Fig.2

PLATE XIV

Fig. 1. Peridotite, 1,100 yards south-east by east of the summit of Minishal. The rock consists of numerous, partly serpentinised olivines enclosed poikilitically in large plates of augite. Some interstitial plagioclase is present. (See pp.138-141). Ordinary Light. x 17.

Fig. 2. Veins of granulitised plagioclase traversing a large plagioclase crystal in the harrisite, 600 yards north-east of Dornabac Stables. (See pp.150-152). Crossed Nicols. x 17.

PLATE XIV

Fig.1

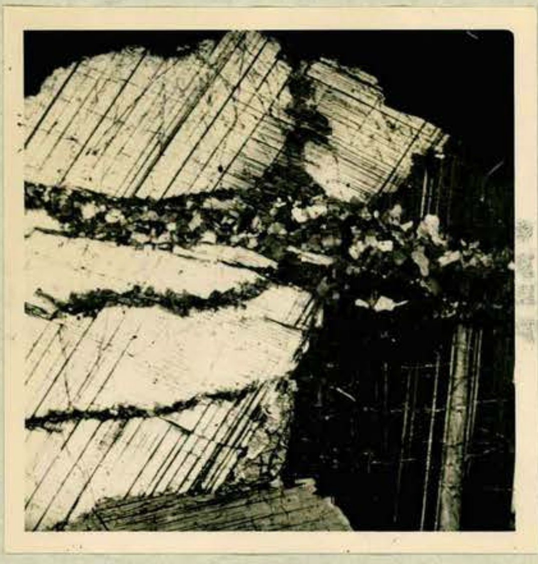

Fig.2

PLATE XV

Fig. 1. Granulitised veinlets of plagioclase, olivine, augite, magnetite and biotite traversing the harrisite, 600 yards north-east of Dornabac Stables. (See pp. 150 - 152). Crossed Nicols. x 17.

Fig. 2. The same field in ordinary light. x 17.

PLATE XV

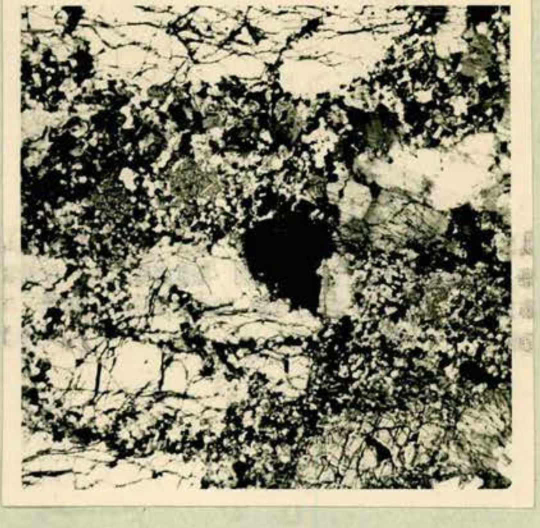

Fig.1

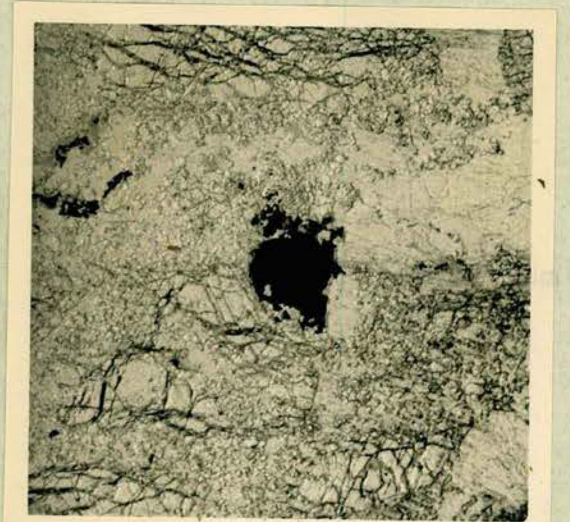

Fig.2

PLATE XVI

Fig. 1. Granulitised vein of plagioclase, olivine, augite, magnetite and biotite traversing the harrisite, 600 yards north-east of Dornabac Stables. (See pp. 150-152). Ordinary Light. x 17.

Fig. 2. The same field figured under crossed Nicols. x 17.

PLATE XVI

Fig.1

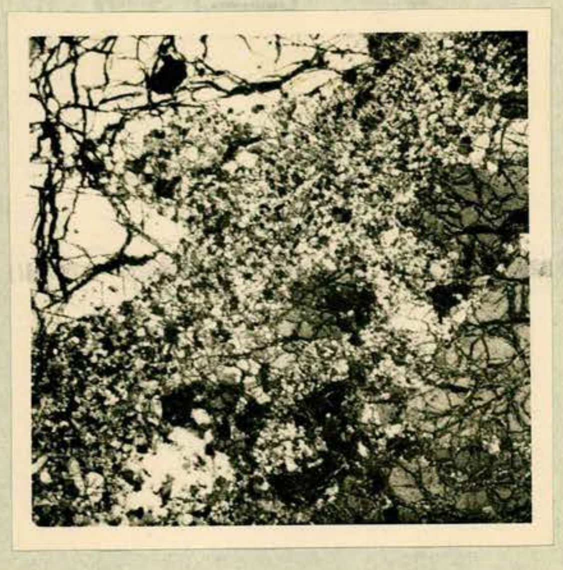

Fig.2

PLATE XVII

Gabbro, 700 yards east by north of Harris Lodge.

Fig. 1. Rounded olivine crystals are partly set in a plexus of plagioclase laths and partly included poikilitically within large augites. Some accessory magnetite is present. (See pp. 152-159). Ordinary Light. x 17.

Fig. 2. The same field as Fig. 1 as seen through crossed Nicols. x 17.

PLATE XVII

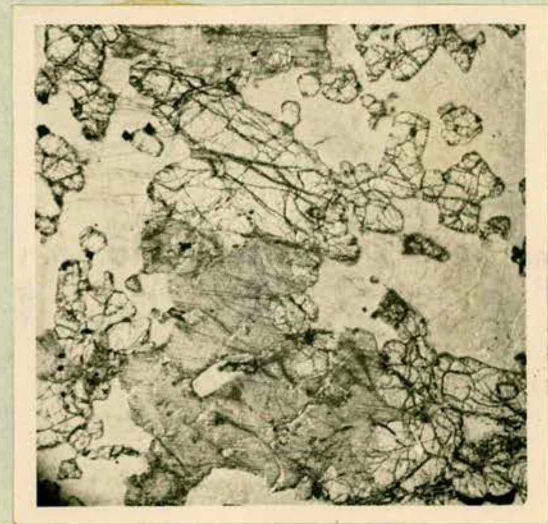

Fig.1

Fig.2

Plates XVIII to XXV illustrate in succession the various transitional zones from the bleached and indurated Torridonian Sandstone to the graphophyre.

PLATE XVIII

Bleached and indurated Torridonian Sandstone (See pp. 36-38).

Fig. 1. 300 yards to the north of the northern exposures of graphophyre on the eastern face of Minishal. The rock consists of quartz and turbid orthoclase grains and small grains of magnetite. Little cement is present and some of the grains are partly sutured together. Ordinary Light. x 17.

Fig. 2. The same field under crossed Nicols. The suturing together of the quartz grains is seen on the left of the field. x 50.

PLATE XVIII

Fig.1

Fig.2

PLATE XIX

Zone A. (See p.39)

Fig. 1. The rock consists of quartz and orthoclase grains with some relatively large crystals of magnetite. A small proportion of biotite is present near the magnetite. Ordinary Light. x 50.

Fig. 2. The same field under crossed Nicols. x 50.

PLATE XIX

Fig.1

Fig.2

PLATE XX

Zone B. (See pp. 39-40).

Fig. 1. Small veinlets of newly-formed orthoclase have penetrated between the quartz grains. (This photomicrograph, like Plate XIX, fig. 1, was taken with the tube slightly raised to show the Becke Line in the quartz. Magnetite and biotite and detrital grains of orthoclase are also present. Ordinary Light. x 50.

Fig. 2. The same field under crossed Nicols. x 50.

PLATE XX

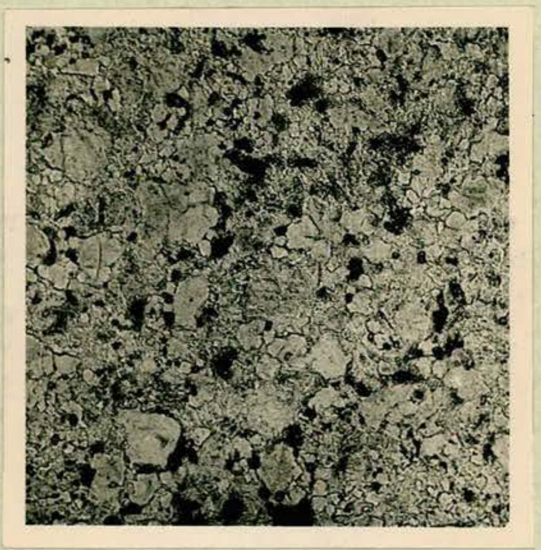

Fig.1

Fig.2

PLATE XXI

Northern part of Zone C. (See pp. 41-42)

Fig. 1. Crystals of biotite and magnetite have developed and small grains of hypersthene with chloritised margins are present. Much orthoclase is now present. Ordinary Light. x 50.

Fig. 2. The same field under crossed Nicols. x 50.

PLATE XXI

Fig.1

Fig.2

PLATE XXII

Southern part of Zone C. (See pp. 41-42).
(See also Plate XXVIII, Fig. 2).

Fig. 1. Crystals of biotite, magnetite, and hypersthene lie in a matrix of quartz and orthoclase. The ferromagnesian minerals are now very abundant. Ordinary Light. x 50.

Fig. 2. The same field under crossed Nicols. x 50.

PLATE XXII

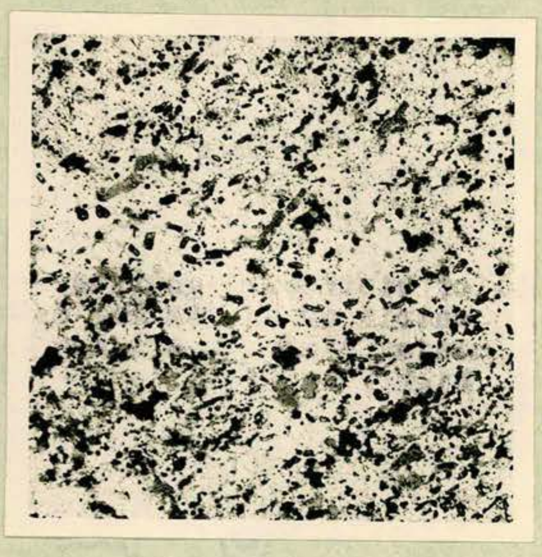

Fig.1

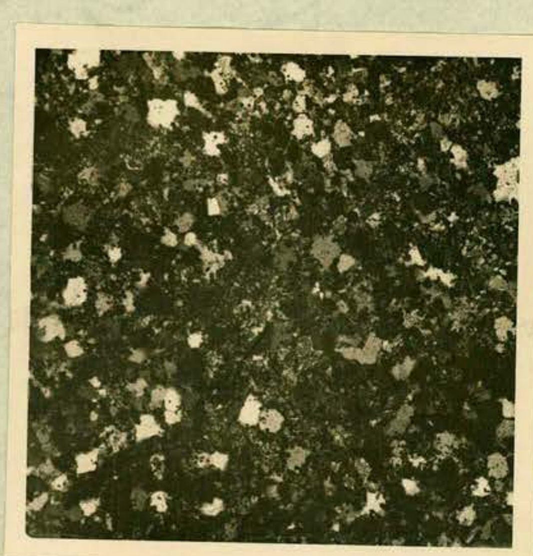

Fig.2

PLATE XXIII

Zone D. (See pp. 42-44).

Fig. 1. A quartzo-feldspathic pod occupies the centre of the field. By its growth this pod has concentrated the mafic minerals - hornblende, magnetite and biotite - around its margins. Large porphyroblasts of turbid orthoclase occur in the right and lower right of the field. Ordinary Light. x 50.

Fig. 2. The same under crossed Nicols. The right-hand part of the pod is seen to be intergrown quartz and orthoclase whereas the left-hand part is largely turbid orthoclase. x 50.

PLATE XXIII

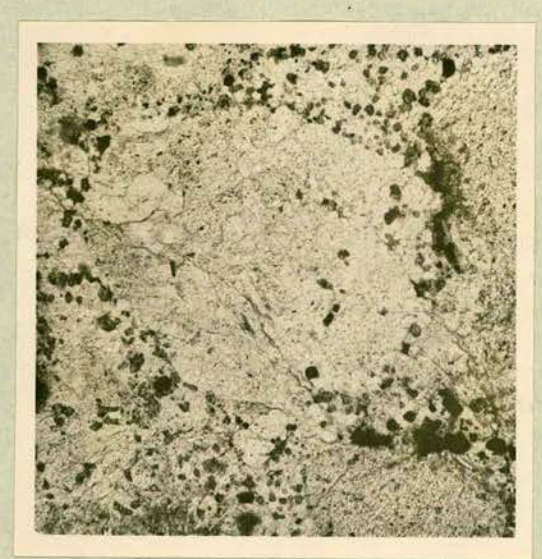

Fig.1

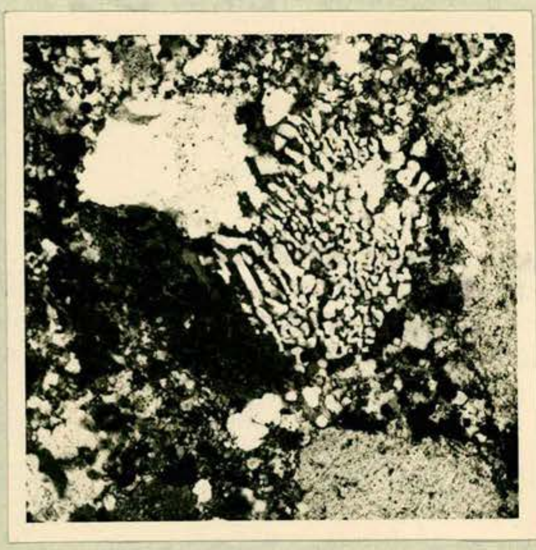

Fig.2

PLATE XXIV

Zone E. (See pp. 44-45).

Fig. 1. Two large, euhedral porphyroblasts of oligoclase occupy the centre and the upper left of the field. They lie in a matrix consisting largely of intergrown quartz and orthoclase with subsidiary hornblende, magnetite and apatite. Ordinary Light. x 50.

Fig. 2. The same field under crossed Nicols. x 50.

PLATE XXIV

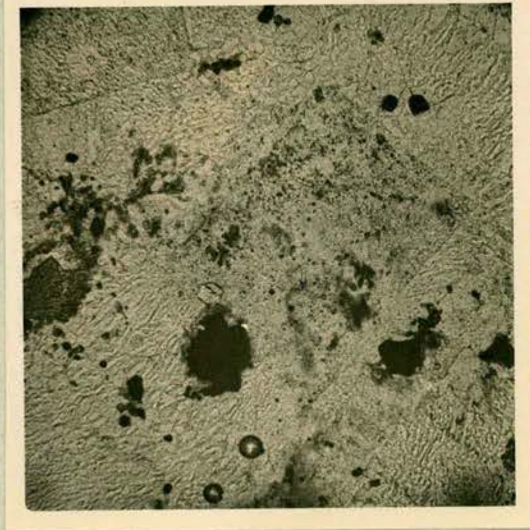

Fig.1

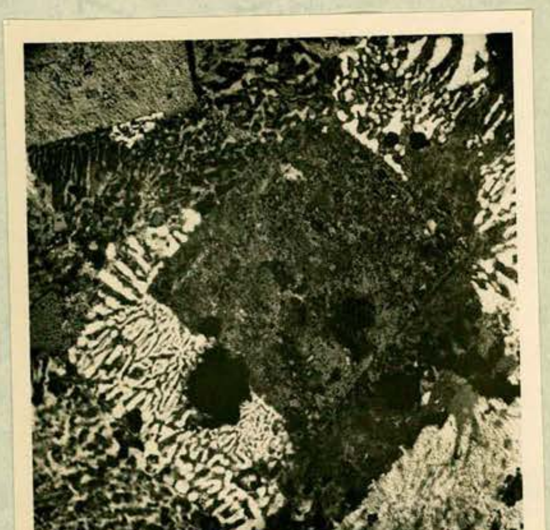

Fig.2

PLATE XXV

Graphophyre. (See pp. 45-50).

Fig. 1. Micropegmatite occupies the greater part of the field. Two porphyroblasts of highly turbid plagioclase occurs in the lower part and in the upper right of the field and grains of magnetite are present. Ordinary Light. x 50.

Fig. 2. The same field under crossed Nicols. x 50.

PLATE XXV

Fig.1

Fig.2

Plates XXVI and XXVII show oligoclase crystals in the micrographite. The crystals are enveloped in finely intergrown quartz and orthoclase and their margins are characterised by numerous rectangular indentations. These indentations are filled with the intergrowth and are believed to have been formed by the partial replacement of the plagioclase by quartz and orthoclase. All the figured oligoclases are typical of the microgranite except those shown in Plate XXVII, Fig. 2 where the degree of replacement is more typical of the plagioclase of the graphophyre. (See pp. 47-49; 54-56).

PLATE XXVI

Fig. 1. Microgranite. An oligoclase crystal. the margin of which shows numerous rectangular indentations, lies in a position of extinction slightly to the left of the centre of the field. Crossed Nicols. x 50.

Fig. 2. Microgranite. The oligoclase in the upper left of the field has been almost completely replaced and has been divided, as seen in thin section, into two separate portions. The oligoclase in the centre of the field has also been divided into two portions, each of which has a much indented outline. Crossed Nicols. x 50.

PLATE XXVI

Fig.1

Fig.2

PLATE XXVII

Fig. 1. Microgranite. A highly replaced oligoclase crystal, cut almost perpendicular to its _a_-axis, lies in the centre of the field. The peripheral portion of the crystal has been breached in two places and the core has been extensively converted to intergrown quartz and orthoclase. Crossed Nicols. x 50.

Fig. 2. Microgranite. Two oligoclase crystals (dark) which have suffered slight replacement by intergrown quartz and orthoclase lie in the centre of the field. Although this photomicrograph was taken of the microgranite, the degree to which the oligoclase has been replaced is more typical of the graphophyre. (The plagioclase of the graphophyre is not figured as it is highly turbid and the indentations tend therefore to be obscure). Crossed Nicols. x 50.

PLATE XXVII

Fig.1

Fig.2

PLATE XXVIII

Fig. 1. Mylonitised Torridonian Sandstone. This rock occurs along the large reverse fault which separates the graphophyre from the Torridonian Sandstone to the north. The large fragments are mainly quartz (clear); some orthoclase fragments (turbid) also occur. The dark groundmass of the rock is composed of finely comminuted particles of the same minerals with, in places, some glass. (Ordinary Light. x 50). (See pp. 33-34).

Fig. 2. Transitional rock from Zone C. Minute prisms of apatite, grains of hypersthene with chloritised margins, irregular flakes of biotite, and grains of magnetite are set in a groundmass of quartz and orthoclase crystals. (Ordinary Light. x 160). (See pp. 41-42).

PLATE XXVIII

Fig.1

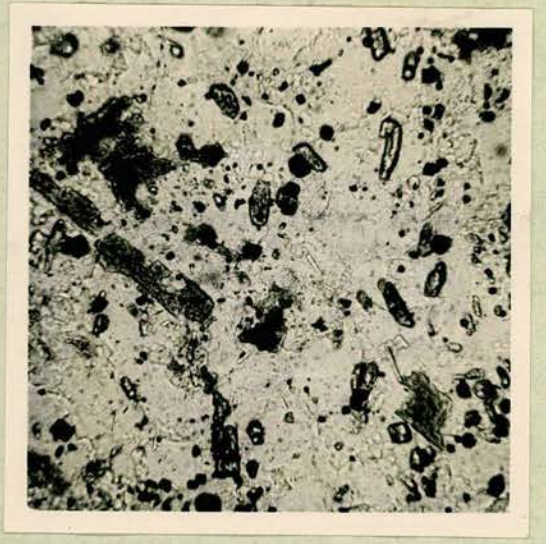

Fig.2

Plates XXIX, XXX, and XXXI Fig. 1. are photomicrographs of different parts of one specimen of the basic hybrid rocks between the graphophyre and the basic plutonic rocks. This specimen was collected on the shore a few yards north of the mouth of the Abhainn Fiachannis. (See pp. 167 - 173).

PLATE XXIX

Fig. 1. Aplitic matrix. The rock consists of quartz and turbid orthoclase with scattered crystals of magnetite which probably represent finely comminuted basic material. Ordinary Light, x 17.

Fig. 2. Small basic fragment which has suffered much metamorphism and metasomatism. It now consists of scattered grains of magnetite and augite. Ordinary Light. x 17.

PLATE XXIX

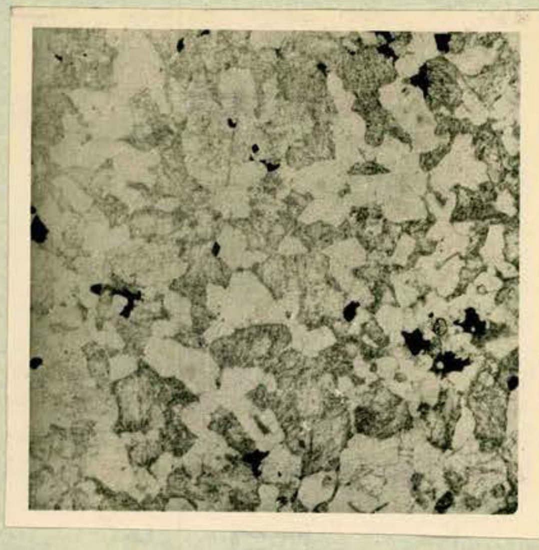

Fig.1

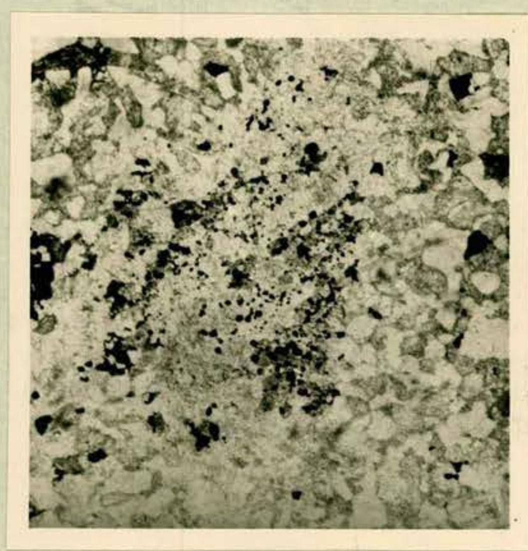

Fig.2

PLATE XXX

(See Plate XXIX).

Fig. 1. Fragment of ophitic dolerite. The augite is much clouded by minute inclusions probably of magnetite and the plagioclase is highly zoned from a calcic core to a more sodic margin. (See pp. 167-173). Ordinary Light. x 50).

Fig. 2. Pyroxene granulite. The rock consists of granules of augite, oligoclase, and magnetite with accessory amounts of apatite. Recrystallisation has taken place and is almost complete. (See pp. 167-173). Ordinary Light. x 50.

PLATE XXX

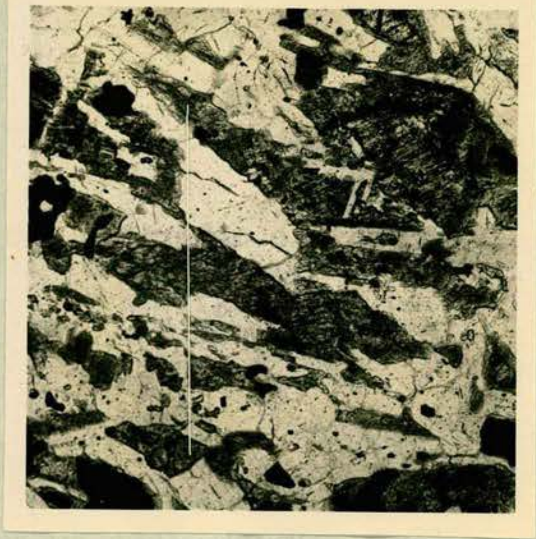

Fig.1

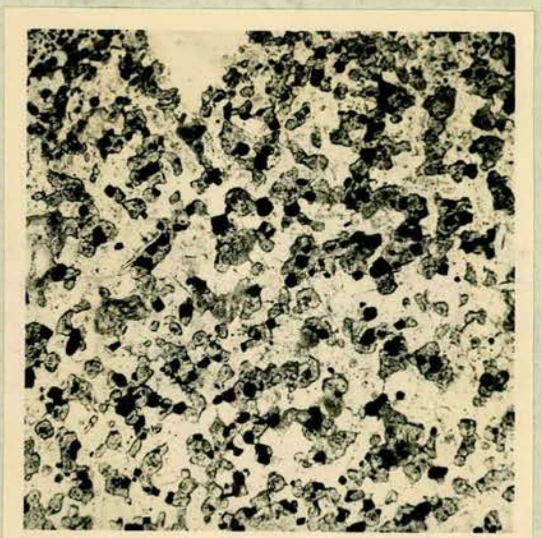

Fig.2

PLATE XXXI

Fig. 1. Fine-grained pyroxene granulite. The rock has been completely recrystallised and consists of almost equidimensional granules of pale brown augite, oligoclase, brown biotite and magnetite. (See pp. 171-172). Ordinary Light. x 50.

Fig. 2. Metamorphosed gabbro in contact with the basic hybrid rocks a few feet from the locality where the specimen figured in Plates XXIX, XXX, and XXXI, Fig. 1 was collected. The rock consists of large, partly serpentised olivines, brown augite dusted with inclusions of iron ore and other opaque material, zoned labradorite and magnetite. (See pp. 173-175). Ordinary Light. x 17.

PLATE XXXI

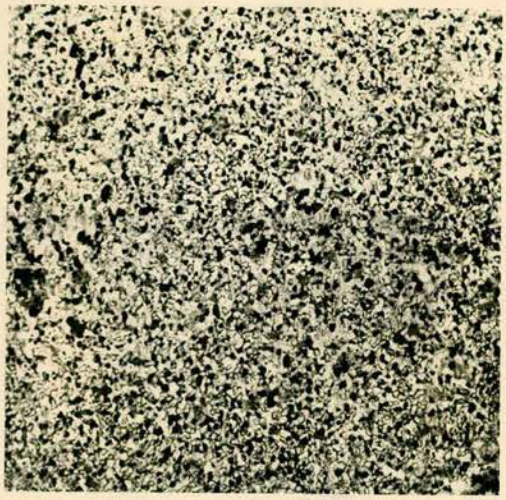

Fig.1

Fig.2

PLATE XXXII

Fig. 1. Metamorphosed gabbro in contact with the basic hybrids to the north of the mouth of the Abhainn Fiachannis. The minerals present are partly serpentised olivine, partly uralitised augite, zoned labradorite and magnetite. (See pp. 173-175). Ordinary Light. x 17.

Fig. 2. Block of metamorphosed basalt containing numerous large phenocrysts of plagioclase in a matrix of what is now pyroxene granulâte. This block, which apart from the effects of metamorphism is petrographically identical with several dykes (See Plate XXXIX, Fig. 1), was collected a few feet from the locality of the specimen figured immediately above. No dykes of this rock are known in the vicinity. (See pp. 168-169). Crossed Nicols. x 17.

PLATE XXXII

Fig.1

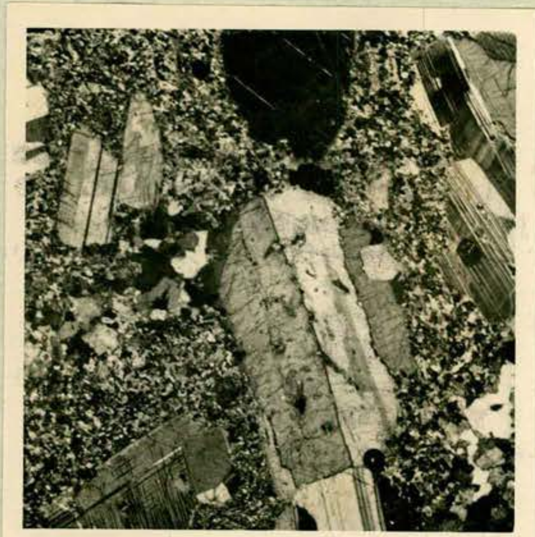

Fig.2

PLATE XXXIII

Basalt block from the basic hybrid rocks near Dornabac Stables. (See pp. 172-173).

Fig. 1. Glassy margin of the block (dark) in contact with the aplitic matrix. Ordinary Light. x 50.

Fig. 2. Crystalline centre of the block consisting of oligoclase, small augite granules and much magnetite. No glass is present. Ordinary Light. x 50.

PLATE XXXIII

Fig.1

Fig.2

PLATE XXXIV

Lower Basalt Lavas from West Minishall
(See p. 112).

Fig. 1. Basal flow. Phenocrysts of plagioclase and olivine lie in a groundmass of plagioclase, augite and magnetite. A very small proportion of olivine is present in the groundmass. Ordinary Light. x 50.

Fig. 2. Third flow. A glomeroporphyritic aggregate of plagioclase and olivine lies in a groundmass of plagioclase, aguite and magnetite. Ordinary Light. x 17.

LATE XXXIV

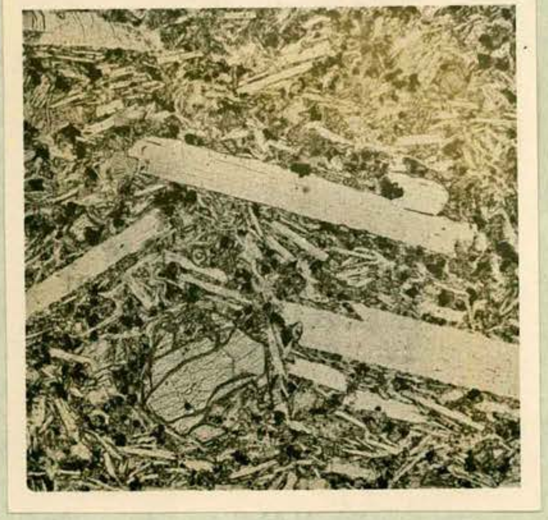

Fig.1

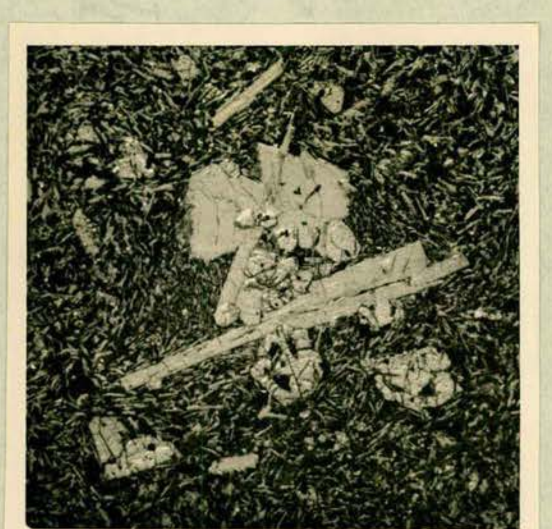

Fig.2

PLATE XXXV

Lower Mugearite Lava from Fionchra.
(See p.112).

Fig. 1. Plagioclase phenocryst in a groundmass of plagioclase microlites and brown glass. Ordinary Light. x 50.

Fig. 2. Chlorite-filled amygdale (centre of field) surrounded by tangentially arranged plagioclase microlites. Ordinary Light. x 50.

PLATE XXXV

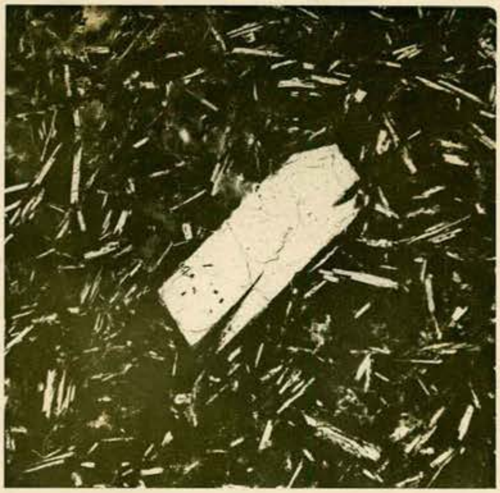

Fig.1

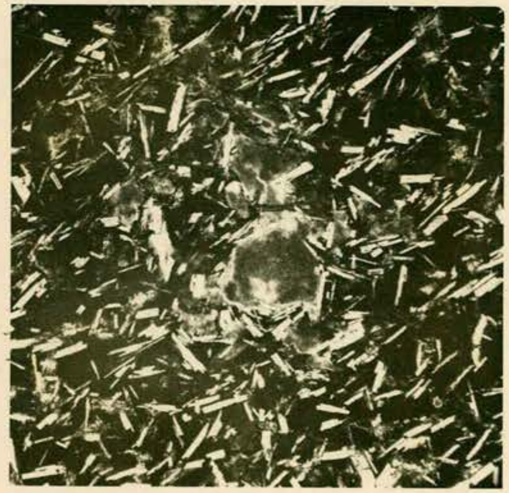

Fig.2

PLATE XXXVI

Fig. 1. Upper Basalt Lava, 200 feet above the base of the lava pile of Orval. The rock consists of plagioclase, sub-ophitic augite, olivine, magnetite and sparse apatite crystals. (See p. 113). Ordinary Light. x 50.

Fig. 2. Lowest of the Upper Mugearite Lava Flows, Fionchra. Minute lath shaped sections of plagioclase are set in a dark brown glassy matrix. (See pp. 113-114). Ordinary Light. x 160.

PLATE XXXVI

Fig.1

Fig.2

PLATE XXXVII

Post-Granitic Dykes and Sheets.

Fig. 1. Ophitic Dolerite. Tabular plagioclases are enclosed partly or wholly in large ophitic crystals of augite. Olivine, magnetite, and secondary chlorite, are also present. (See pp. 129-130). Ordinary Light. x 50.

Fig. 2. Granular Dolerite. The rock consists of plagioclase enclosing rods of glass or of augite, grains of augite, magnetite and secondary chlorite. (See pp. 129-130). Ordinary Light. x 50.

PLATE XXXVII

Fig.1

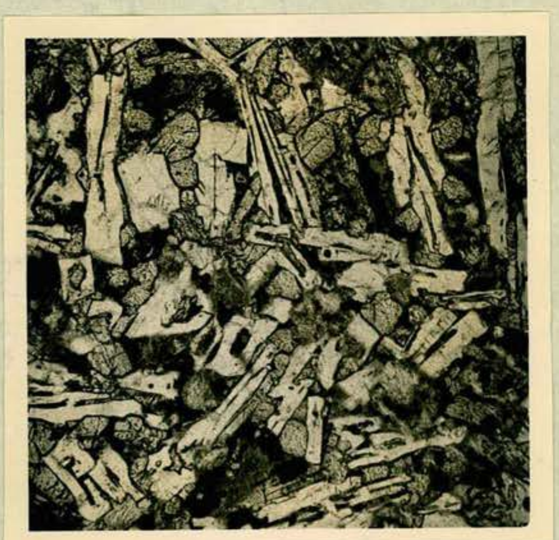

Fig.2

PLATE XXXVIII

Post-Granitic Dykes and Sheets. (contd.).

Fig. 1. Augite-Andesite. The rock consists of oligoclase, augite, magnetite and secondary chlorite. (See pp. 132 - 133). Ordinary Light. x 50.

Fig. 2. Mugearite-Tachylyte. Crystallites of augite and grains of magnetite lie in a brown glassy groundmass. (See pp. 131 - 132). Ordinary Light. x 50.

PLATE XXXVIII

Fig.1

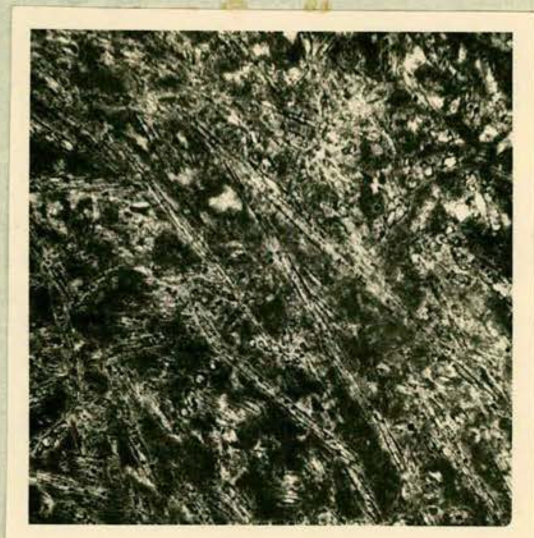

Fig.2

PLATE XXXIX

Post-Granitic Dykes and Sheets. (contd.).

Fig. 1. Porphyritic Basalt. Large phenocrysts of plagioclase lie in a groundmass of plagioclase, augite, magnetite and secondary chlorite. (See pp. 130-131). Crossed Nicols. x 17.

Fig. 2. Porphyritic Basalt. A plagioclase phenocryst which has been partially fused along cracks. The fused areas appear abnormally turbid. (See pp. 130-131). Ordinary Light. x 50.

PLATE XXXIX

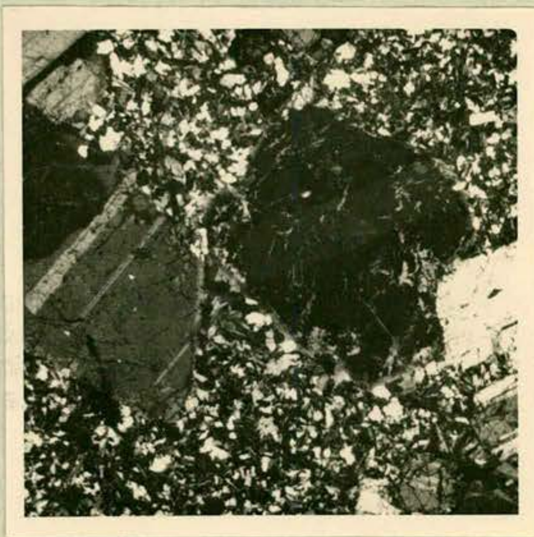

Fig.1

Fig.2

PLATE XL

Fig. 1. Granular Basalt Dyke. The rock consists of plagioclase, partly chloritised augite and magnetite. (See pp. 129 - 130). Ordinary Light. x 50.

Fig. 2. Glassy margin of a dyke injected into sheared gabbro. Veinlets of glass containing small plagioclases traverse the comminuted material. Ordinary Light. x 17. (See pp. 128, 130).

PLATE XL

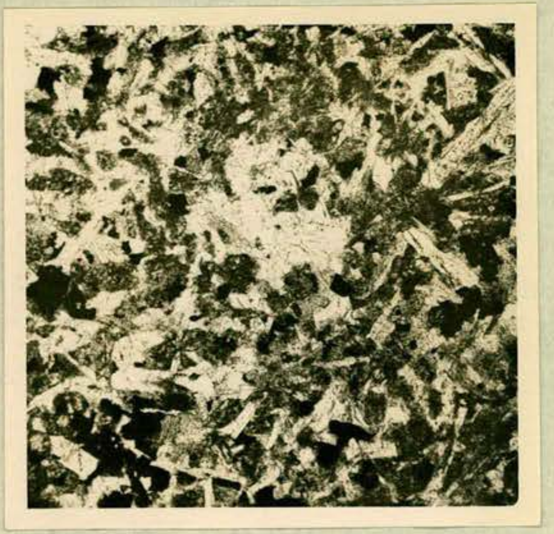

Fig.1

Fig.2